GEOLOGY OF THE ALTA STOCK, UTAH

Thesis by

John C. Wilson

In Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy

California Institute of Technology
Pasadena, California

1961

ACKNOWLEDGEMENTS

The continued interest, suggestions and helpful criticism of Dr. L. T. Silver are greatly appreciated. The writer also wishes to thank Dr. A. L. Albee and Dr. J. A. Noble for advice and criticism of an early draft of this thesis.

The many thin sections used in this study were prepared by Mr. R. von Huene. Mr. A. A. Chodos instructed the writer in emission spectrographic analysis. Miss E. Godijn made four general trace-element analyses and three analyses specifically for fluorine. Dr. D. Maynes made four gravimetric chemical analyses. Mr. D. Shakel assisted the writer for two weeks in the field during the summer of 1960. The officials of the United Park City Mines Co. and of the New Park Mining Company gave freely of their time and facilities, and contributed much to the writer's knowledge of the geology of the Park City district.

The work was made possible by a fellowship from the Kennecott Copper Corporation held by the writer during the years 1959-60 and 1960-61 and the Harvey Mudd Summer Fellowship during 1958, 1959 and 1960.

ABSTRACT

The Alta stock of granodiorite is closely associated in space and time with many of the Pb, Zn and Ag ore deposits of the Park City-Cottonwood mining area in the central Wasatch Mountains, Utah. The purpose of this study was to determine if fractional crystallization of the Alta magma ultimately resulted in a metal-rich ore-forming fluid.

The Alta magma was intruded in two pulses into pre-Triassic sedimentary rocks at a depth of approximately 21,000 feet and at a temperature in excess of 720°C. Detailed study of texture indicates that the first phase of magma solidified with a nonporphyritic texture, crystallizing from the wall progressively toward the center of the stock. The rock at the wall is rich in mafic minerals but grades inward within a few hundred feet to light-gray medium-grained biotite-hornblende granodiorite. Early in the history of the first pulse of magma, convection currents carrying growing crystals of early minerals formed stratified gravity accumulations rich in hornblende, biotite, sphene, magnetite and apatite. These layered masses were subsequently broken and displaced. They now form tabular inclusions of mafic layered granodiorite in the light-gray nonporphyritic granodiorite.

At a late stage in the crystallization history, the Alta stock had an essentially solid shell of nonporphyritic granodiorite at least 1200 feet thick that surrounded a partially liquid but semirigid crystal mush at the center of the stock. Structural adjustments at this late stage resulted in close-space jointing and emplacement of aplite-pegmatite dikes in the nonporphyritic granodiorite shell. After emplacement of the dikes but before the interstitial liquid of the magma at the center of the stock had completely crystallized, the semi-rigid crystal mush and solid shell were intruded by a second pulse of the magma. The distribution of strongly porphyritic texture indicates that loss of volatiles through fractures in the overlying material caused this later phase of the magma to finish crystallization with a fine-grained groundmass. Modal analyses supported by gravimetric chemical analyses show that the porphyritic granodiorite has a slightly more silicic composition than the nonporphyritic granodiorite.

The Flagstaff-Emma ore zone in the Little Cottonwood district is on the trend of a westward dikelike projection of the porphyritic granodiorite. The fluids that were released during the emplacement of this late phase of the magma conceivably may have been the same fluids that deposited the ore minerals in the Flagstaff-Emma ore zone.

In order to determine the trend of the ore-metals during crystallization of the Alta magma, 76 mineral separates of orthoclase, plagioclase, biotite, hornblende, magnetite, sphene, quartz and chlorite were analyzed by the emission spectrographic method for Cu, Pb, Zn, Ag, Co, Ni and Sn. Comparison between samples of the same mineral show that Co and Ni are slightly less abundant and Cu, Pb and Sn are more abundant in the later phases of the Alta igneous suite. No trend is apparent for Ag and Zn. Cu, Co, Ni, Ag and Zn were added to the solid phases of the rock during chloritic alteration.

The release of volatiles associated with the late-stage intrusion of porphyritic granodiorite, the structural relation of the adjacent ore deposits to this porphyritic granodiorite and the trend in trace-element abundances suggest that an ore-forming fluid may have been produced at a late stage in the crystallization of the Alta stock.

TABLE OF CONTENTS

FIGURES

TABLES

PLATES

INTRODUCTION

Nature of the Investigation

The Alta stock is one of several Tertiary intrusives in the central Wasatch Mountains, Utah, which are closely associated in space and time with many of the ore deposits of the Park City-Cottonwood mining area (Plate 1). This mineralized area, which has produced almost $500 million in lead, silver, zinc, gold and copper ores, contains the only major ore deposits and the only Tertiary intrusive rocks in the central Wasatch Mountains. The purpose of this research has been to attempt to clarify possible genetic relations between these ore deposits and igneous rocks, and especially to establish if there was a continuum of phenomena between crystallization of the igneous rocks and the deposition of the adjacent ore deposits.

The first phase of the research was a reconnaissance examination of the geology and petrography of the igneous rocks of the district. The Alta stock was chosen for detailed geologic and chemical study on the basis of this investigation for two reasons: (1) the close relation in time and space to the adjacent ore deposits and (2) the rather extensive exposures of relatively unweathered and unaltered rocks.

The second part of the study consisted of mapping the geology of the Alta stock. Field work was completed in 91 days during the summers of 1958, 1959 and 1960. Nineteen days were spent in reconnaissance investigation of the igneous rocks and ore deposits in all parts of the Park City-Cottonwood area and 72 days in geologic mapping and sample

collection specifically in the Alta stock. Most sample locations were originally plotted on the 7-1/2 minute Brighton quadrangle (U.S. Geol. Survey, 1955, 1:24,000) in the initial reconnaissance investigation. An enlargement (1:12,000) of the more detailed Cottonwood quadrangle (U.S. Geol. Survey, 1938, 1:25,000) was used as a base for detailed mapping and sampling of the Alta stock.

The third part of the work was a study of the petrography of the Alta stock. Study of specimens was coordinated with new collecting and mapping. Forty-eight modal analyses and many observations and measurements on texture were recorded from the 150 thin sections of specimens collected in the Alta stock. Optical measurements were made on plagioclase, orthoclase, biotite and hornblende from representative samples.

The fourth part of the work consisted of gravimetric chemical and spectrochemical analyses of rocks and minerals of the Alta stock. Seventy-six mineral concentrates of orthoclase, plagioclase, biotite, hornblende, quartz, magnetite and chlorite were separated from 16 rocks of the Alta stock. The mineral concentrates and eight of the rocks from which they were obtained were analyzed by emission spectrographic techniques for lead, copper, zinc, silver, cobalt, nickel and tin. Gravimetric chemical analyses were obtained of samples of two rocks, one biotite concentrate and one hornblende mineral separate.

Location and Accessibility

The Alta stock crops out in the highest part of the central Wasatch Mountains, 25 miles southeast of Salt Lake City, Utah (Fig. 1).

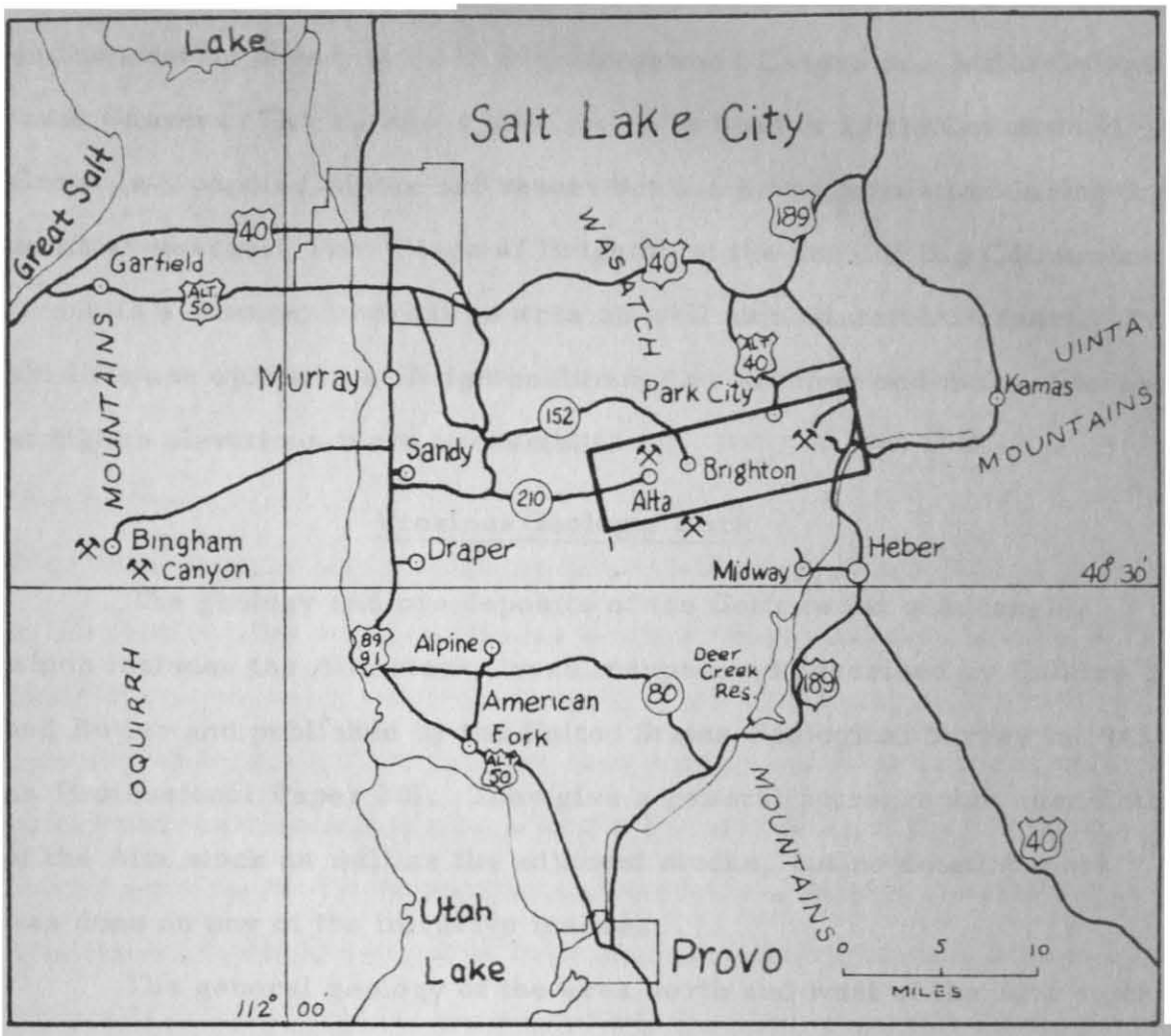


Figure 1. Index map of the Park City - Cottonwood area, Utah.

Elevations in the area range from 8600 feet at Alta to 10,795 feet on Mt. Wolverine (Plate 2). The area is accessible from Salt Lake Valley on the west by paved roads in Big Cottonwood Canyon and Little Cottonwood Canyon. The village of Alta near the head of Little Cottonwood Creek is a popular winter ski resort but has a low population during the summer season. The village of Brighton at the head of Big Cottonwood Creek is a summer recreation area as well as a winter ski resort. Two ski lifts are operated at Brighton during the summer and make outcrops at higher elevations more accessible.

Previous Geologic Work

The geology and ore deposits of the Cottonwood quadrangle, which includes the Alta stock, were mapped and described by Calkins and Butler and published by the United States Geological Survey in 1943 as Professional Paper 201. They give a general petrographic description of the Alta stock as well as the adjacent stocks, but no detailed work was done on any of the intrusive masses.

The general geology of the area north and west of the Alta stock is described in Guidebook to the Geology of Utah, No. 8, entitled "Geology of the Central Wasatch Mountains, Utah", published by the Utah Geological Society in 1952.

REGIONAL SETTING OF THE ALTA STOCK

The sedimentary rocks of the central Wasatch Mountains range from Precambrian to early Tertiary in age. There are over 18,000 feet of Precambrian quartzite and shale; 7,000 feet of Paleozoic carbonate

rocks, quartzite and shale; 16,000 feet of Mesozoic sandstone, shale and conglomerate; and at least 2,000 feet of Tertiary conglomerate and volcanic rock. The age, thickness and lithology of the formations found in the central Wasatch Mountains are given in Table 1. The distribution of Precambrian, Cambrian, Mississippian, Pennsylvanian and Permian and Mesozoic sedimentary rocks is shown on Plates 1 and 2. For further information on the description and distribution of sedimentary rocks in the central Wasatch Mountains, see Boutwell (1913), Calkins and Butler (1943), Crittenden et al. (1952), Baker (1952) and C. L. Wilson (1960).

The Alta stock is one of five Tertiary intrusive masses which lie at the intersection of two of the major structural elements in central Utah: the north-south trending Wasatch Mountains uplift and the east-west trending Uinta arch. The igneous rock bodies lie on or near the western extension of the anticlinal axis of the Uinta structure. The bodies are, from west to east, the Little Cottonwood stock of quartz monzonite, the Alta stock of granodiorite, the Clayton Peak stock of diorite, the Ontario stock of granodiorite, and the Park City complex of "quartz diorite porphyry". The Ontario stock is a new name proposed here for the pinkish gray porphyritic rocks which are exposed in McHenry Canyon, south of Park City, and also for the nonporphyritic rocks exposed at depth in several thousand feet of workings of the Ontario mine. This stock is mapped as a unit of the Park City complex by C. L. Wilson (1960). The Ontario stock intrudes the "quartz diorite porphyry" of the Park City complex on the 800 level of the Mayflower mine.

TABLE 1. STRATIGRAPHY OF THE PARK CITY-COTTONWOOD AREA

(after Crittenden et al., 1952)

TERTIARY SYSTEM

Knight (?) formation: several thousand feet thick, reworked from underlying beds.

Tertiary (?) andesite: red weathering flows and breccias.

Fowkes (?) formation: 800 feet, poorly consolidated red sandstone, sandy limestone and water-laid tuff.

Almy (?) conglomerate: contains boulders of Precambrian and Tintic quartzite.

(Unconformity)

CRETACEOUS SYSTEM

Cretaceous (?) conglomerate: contains cobbles of Frontier sandstone, Weber quartzite and Carboniferous limestone. The conglomerate is folded into a syncline north of the Park City-Cottonwood area and lies in angular unconformity on all formations from Twin Creek to Frontier.

(Unconformity)

Frontier formation: 8,000+ feet, pale yellowish brown sandstone, interbedded with yellow or pale-red tuffaceous clay and a few beds of conglomerate.

Kelvin formation: 1,500 feet, pale reddish brown to purple siltstone, with smaller amounts of sandstone and a few very prominent conglomerates.

JURASSIC SYSTEM

Morrison (?) formation: 100 feet, white algal limestone.

Preuss formation: 1,000 feet, pale-red shale and sandstone.

Twin Creek limestone: 2,800 feet, pale-gray limestone interbedded with greenish limy shale.

Nugget sandstone: 800 feet, pale terra-cotta, strongly cross-bedded sandstone.

TABLE 1. (Continued)

TRIASSIC SYSTEM

Ankareh formation: 1,550 feet, red to purple shale and sandstone with white gritty quartzite in middle.

Thaynes formation: 1,000 feet, gray limestone, sandstone and greenish shale.

Woodside shale: 1,000 feet, dark-red shale and siltstone.

PERMIAN AND PENNSYLVANIAN SYSTEMS

Park City formation: 600 feet, limestone, limy shale, and sandstone.

PENNSYLVANIAN SYSTEM

Weber quartzite: 1,200 to 1,500 feet, pale-gray fine-grained quartzite or quartzitic sandstone, interbedded with limy and dolomitic quartzite and sandstone, and buff-gray cherty limestone and dolomite.

Morgan (?) formation: 200 to 300 feet, pale-gray limestone with pink chert and minor amounts of greenish shale and quartzite.

MISSISSIPPIAN SYSTEM

"Doughnut" formation: 300 feet, sandstone, black shale, thin-bedded limestone.

Humbug formation: 200 feet, alternating limestone, dolomite, and brown sandstone.

Deseret limestone: 800 to 900 feet, cherty dolomite and limestone, dark-colored shale at base.

Madison limestone: 450 feet, blue-gray and blackish-gray limestone and dolomite.

Unnamed Basal Mississippian dolomite: 120 to 150 feet, pale-gray and dark lead-gray massive dolomite.

(Unconformity)

CAMBRIAN SYSTEM

Maxfield limestone: up to 1,000 feet; light-gray to black dolomite, dark mottled argillite with nodules of white limestone; pale-gray to sooty-black dolomite.

TABLE 1. (Continued)

Ophir shale: 400 feet, dull olive-green micaceous shale, blue-gray limestone with crinkled laminations, yellowish-brown limy shale with blocky fracture.

Tintic quartzite: 800 feet, white or pinkish quartzite, pebble conglomerate at the base.

(Unconformity)

PRECAMBRIAN SYSTEM

Mutual formation: medium- to coarse-grained red-purple quartzites and variegated red and green shales.

(Unconformity)

Mineral Fork tillite: 0 to 3000 feet, black tillite, consisting of boulders, cobbles and pebbles of quartzite, limestone, or granitic rocks in an abundant sandy matrix; black or dark-gray varved slate or shale; dark-gray quartzite.

(Unconformity)

Big Cottonwood series: 16,000+ feet, alternating rusty-weathering white or greenish quartzites and variegated red, greenish and blue-purple shales.

Little Willow series: strongly folded gneissic quartzites, quartz-mica schists and stretched-pebble schists, intruded by basic igneous rocks now altered to amphibolites and chlorite amphibole schists.

In addition to the intrusive rocks, andesite flows crop out on the eastern side of the range. These flows rest unconformably on folded Paleozoic formations and diorite porphyry of the Park City complex. The andesite is listed as Tertiary (?) by Crittenden et al. (1952).

The stocks intrude rocks as young as the Ankareh formation of Triassic age and hence are post-Triassic in age (Boutwell, 1913). Age determinations by the lead-alpha method (Jaffe et al., 1959) on zircons from igneous rocks of the central Wasatch Mountains are the following; Little Cottonwood stock 46 m.y. (millions of years), Alta stock, 54 m.y., and the Clayton Peak stock 40 and 48 m.y.

Modal data and published chemical analyses of the igneous rocks in the area are found in Tables 2 and 3.

The largest and most quartz-rich igneous rock body in the central Wasatch Mountains is the Little Cottonwood quartz monzonite. It crops out in a roughly equidimensional area of slightly over 25 sq mi which extends east from the western front of the Wasatch Mountains to the village of Alta. The rock is coarsely porphyritic with 0.5- to 6.0-cm phenocrysts of K-feldspar in a granular groundmass of 0.5- to 4.0-mm plagioclase, quartz, biotite and hornblende. Sharp (1958) describes the petrography of the quartz monzonite and tungsten mineralization in the stock.

The major minerals of the Alta granodiorite are plagioclase, orthoclase, quartz, biotite, and hornblende. The grain size of the granodiorite varies from less than 0.5 mm to 10.0 mm. The Alta

TABLE 2. MODAL COMPOSITION OF MAJOR IGNEOUS ROCK BODIES

	volume %				
	1	2	3	4	5
Plagioclase	42.2	45.8	45.9	48.1	35.2
K-feldspar	18.2	19.1	16.2	17.4	(a)
Quartz	28.5	19.6	3.2	17.6	(a)
Groundmass	--	--	--	--	41.0
Biotite	9.7	5.6	12.2	6.2	4.3
Hornblende	0.3	6.0	13.1	7.0	13.0
Chlorite + epidote	--	1.0	--	0.2	3.9
Clinopyroxene	--	--	4.8	--	--
Orthopyroxene	--	--	0.4	--	--
Magnetite	0.1	1.6	3.1	2.4	2.0
Apatite	0.3	0.5	1.2	0.4	0.4
Sphene	0.7	0.6	--	0.4	--
Other	--	0.2	--	0.4	--
	100.0	100.0	100.1	100.1	99.8
Plag. comp.	An 31	An 37	An 43	An 42	An 50

(a) Groundmass is composed of approximately equal proportions of quartz and K-feldspar.

Column

1. Little Cottonwood quartz monzonite, average of 2 modes, Sharp (1958).
2. Alta granodiorite average of 10 modes.
3. Clayton Peak diorite 1/2 mile northeast of Clayton Peak.
4. Ontario granodiorite face of 1544S crosscut on July 24, 1959.
5. "Diorite porphyry" 0.8 mile SW of Valeo Mine.

TABLE 3. PUBLISHED CHEMICAL ANALYSES OF IGNEOUS ROCKS FROM THE PARK CITY-COTTONWOOD AREA

	L. C.	Alta			C. P.	Park City		Andesite
	1	2	3	4	5	6	7	8
SiO_2	67.02	65.27	63.46	62.16	59.35	59.68	61.64	54.23
Al_2O_3	15.78	15.75	15.93	17.17	16.36	15.61	14.66	17.37
Fe_2O_3	1.56	2.31	2.61	2.26	2.90	2.49	1.95	4.00
FeO	2.80	1.85	2.31	2.78	3.36	2.38	1.68	1.95
MgO	1.09	1.62	2.27	1.81	3.08	2.52	2.55	3.00
CaO	3.31	4.09	4.33	4.70	5.03	4.63	4.65	6.67
Na_2O	3.85	3.92	3.66	3.96	3.73	3.96	2.71	2.96
K_2O	3.67	3.25	3.49	3.58	3.85	2.92	3.07	2.80
H_2O^+	0.63	0.53	0.74	0.60	0.64	} 2.51	} 3.60	3.71
H_2O^-	0.29	0.21	0.27	0.03	0.28			1.60
TiO_2	0.37	0.55	0.62	0.53	0.87	0.62	0.48	0.75
ZrO_2	0.04	0.02	0.03	0.01	0.03	0.01	0.01	0.02
P_2O_5	0.26	0.25	0.16	0.17	0.14	0.29	0.24	0.34
S	0.03	-	-	0.04	-	-	-	-
MnO	0.02	0.10	0.09	0.06	0.07	0.08	0.06	0.10
CO_2	-	tr	tr	-	tr	2.29	2.15	0.33
BaO	0.13	0.11	0.15	0.17	0.16	0.15	0.18	0.15
Cl	-	0.01	0.05	-	0.05	-	-	-
FeS_2	-	0.02	-	-	0.02	0.02	0.32	0.02
SrO	-	0.05	-	-	0.05	0.07	0.06	0.06
	100.85	99.91	100.17	100.03	100.29	100.23	100.00	100.06

TABLE 3. (Continued)

References:

Analyses 1 to 5, Calkins and Butler, 1943, p. 40.
Analyses 6 to 8, Boutwell, 1913, p. 84.

Sample location and description cited in References.

Analysis

1. Quartz monzonite of Little Cottonwood stock, below upper power plant. R. C. Wells, analyst.
2. Granodiorite of Alta stock. W. F. Hillibrand, analyst.
3. Granodiorite, east side of Brighton Gap.[a] W. F. Hillibrand, analyst.
4. Granodiorite of the Alta stock dump of Steamboat tunnel, Snake Creek. Charles Milton, analyst.
5. Quartz diorite of Clayton Peak stock, three-fourths of a mile northeast of Clayton Peak. W. F. Hillibrand, analyst.
6. Quartz diorite porphyry from dike northwest of Daly-West shaft. W. F. Hillibrand, analyst.
7. Quartz diorite porphyry from Valeo mine, Cottonwood Canyon. W. F. Hillibrand, analyst.
8. Andesite from Ontario drain tunnel, 810 feet from mouth. W. F. Hillibrand, analyst.

(a) There is no Brighton Gap on Park City Quad. in U. S. Geological Survey Professional Paper 77.

granodiorite is distinguished from the Little Cottonwood quartz monzonite by its slightly lighter color and finer grain size. The Alta stock intrudes the Clayton Peak stock.

The Clayton Peak stock is composed of dark bluish gray, fine-grained, hypersthene-augite-biotite-hornblende diorite. In contrast to the Alta stock which contains only a few recognizable wall-rock inclusions, the Clayton Peak stock contains numerous large isolated masses of metamorphosed sedimentary rocks. Several of the larger inclusions are shown in Plate 1.

The Ontario stock of granodiorite crops out on the east side of the Wasatch Range, a half mile south of Park City. The stock underlies an area 9000 feet long in an east-west direction and 400 to 2100 feet wide. The plan area of the stock increases rapidly with depth. The approximate outline of the stock in mine workings 2000 feet below the surface is shown on Plate 1. The nearest outcrop of the Alta stock is 3.0 miles due west and the nearest outcrop of the Clayton Peak stock is 1.9 miles west southwest. At the surface the Ontario granodiorite is a medium-grained, pinkish-gray, porphyritic granodiorite with phenocrysts of plagioclase biotite, hornblende and quartz in a light, pinkish-gray groundmass of quartz and K-feldspar. In mine workings, the Ontario stock is composed of medium-grained, medium-gray nonporphyritic granodiorite. This rock has approximately the same modal composition as the Alta granodiorite, (Table 1). The pinkish gray color and slightly larger average grain size distinguish the Ontario granodiorite from the Alta granodiorite.

The Park City igneous complex, with an outcrop area of nine sq. mi., lies south of the Ontario stock and east of the Clayton Peak stock. The rocks in this complex have a wide range of composition and texture but the most abundant rock type is a dark-gray quartz diorite porphyry. The phenocrysts of the porphyry are plagioclase, hornblende, biotite and quartz. These minerals are set in a gray to greenish-black, very fine-grained groundmass which makes up 35 to 50 percent of the rock. The groundmass is composed of quartz and K-feldspar in approximately equal proportions and minor chlorite, magnetite, biotite and hornblende.

The Park City complex contains large isolated masses of quartzite and limestone some of which can be correlated with Paleozoic formations in the wall rocks of the intrusions. Relationships in the Mayflower mine indicate that the intrusion is in part floored by lower Paleozoic formations.

Within the zone of igneous activity and mineralization in the central Wasatch Mountains, there are two principal areas in which base- and precious-metal ore deposits have been worked: (1) the Park City district on the east side of the range and (2) the Big Cottonwood, Little Cottonwood and American Fork districts in the western half of the area shown on Plate 1. Ninety percent of the production has come from the mines of the Park City district. The cumulative metal production for the two areas is given in Table 4, and the approximate location and orientation of the major ore deposits are shown in Plate 1.

The ore deposits are more closely related in time and space to the Ontario and Alta stocks of granodiorite than to any other of the five intrusive masses. The Ontario stock was not used in this study because of its intense hydrothermal alteration and very poor exposure.

The principal minerals of the ore deposits are pyrite, galena, tetrahedrite-tennantite, sphalerite, argentite and the ruby-silver minerals. Most of the ore deposits in the area are classed as mesothermal and consist of fissure fillings on east to northeast fractures and replacement deposits in favorable strata associated with these fissures. Ore is confined to the sedimentary rocks in most of the area, except for the Mayflower mine in which ore deposits have been developed in fissures in and below the quartz diorite porphyry of the Park City complex. Scheelite mineralization in the Little Cottonwood stock is described by Sharp (1958).

Table 4. METAL PRODUCTION FROM THE PARK CITY DISTRICT AND THE COTTONWOOD AREA

District	Cumulative prod. to	Short tons Gold	Silver	Copper	Lead	Zinc
Park City (Uintah)	1955	32	10,200	39,000	1,283,000	422,000
Big Cottonwood Little Cottonwood	1954	1.3	710	8,470	121,000	2,290

Sources of data:

Calkins and Butler (1943)

U.S. Bureau of Mine Mineral Yearbooks for the years 1945 to 1955.

GENERAL GEOLOGY OF THE ALTA STOCK

The Alta stock is at the head of the drainage basins of Little Cottonwood Creek and Big Cottonwood Creek (Pl. 1). The outcrop area of the Alta stock is 4.0 sq mi, which is half as large as the outcrop area of the Clayton Peak stock on the east and one sixth as large as the outcrop area of the Little Cottonwood stock, 1.5 miles to the west. The outcrop pattern is elongate in a northeast-southwest direction. The widest part of the outcrop area is 1.4 miles and is located in the southwestern half of the stock. The stock narrows toward the northeast to 2000 feet and the outcrop pattern curves around the north side of the more equant-shaped Clayton Peak stock.

Mountain glaciation has produced abundant bedrock exposures in the Alta stock in the area between the villages of Brighton and Alta. Glacial deposits separate this main outcrop area from a smaller, more poorly exposed area of quartz monzonite extending northeast of Brighton to Shadow Lake at the head of Thaynes Canyon. Because of the better exposures, nearly all of the field and petrographic studies were done in the part of the stock southwest of Brighton. All conclusions on the origin of the texture and composition of the stock are based on studies in this area.

Rock Types

The Alta stock consists predominantly of a number of varieties of granodiorite, but aplite-pegmatite dikes, leucocratic quartz monzonite dikes, a mafic border phase and mafic layered granodiorite are also recognized in the stock. Aplite-pegmatite dikes are especially abundant

and well exposed in a quarry at the north end of the Twin Lakes Reservoir dam. Leucocratic quartz monzonite dikes are very rare but are exposed at several localities north of Lake Mary. The border phase is especially well exposed where Little Cottonwood Creek crosses the south contact of the Alta stock. Bodies of mafic layered granodiorite are exposed at several localities on the west slope of Mt. Wolverine.

Two major textural varieties of granodiorite are present in the Alta stock; porphyritic and nonporphyritic. A third textural type, subporphyritic, is largely gradational in character between the other two varieties. The general hand specimen appearance of all three varieties is similar and can be described in each case as light-gray, medium-grained, inequigranular biotite-hornblende granodiorite. In general, the nonporphyritic granodiorite is slightly darker, contains more inclusions and is more jointed than the porphyritic granodiorite.

The best exposures of porphyritic granodiorite are found on Mt. Millicent and on the shores of Lake Mary. Nonporphyritic granodiorite and subporphyritic granodiorite are virtually indistinguishable in the field and most readily accessible outcrops in the Brighton Recreation Area are composed of one or the other of these two types.

The differences in texture between the nonporphyritic and porphyritic granodiorite as seen in hand specimen and thin section are shown in Figure 2. In hand specimens of both major textural types, subhedral tablets of multiple-twinned white plagioclase, 1 to 10 mm in length, can be recognized as a major constituent. Smaller grains of white granular feldspar and gray quartz form about 40 percent of the rock. Biotite and

Figure 2. Porphyritic and nonporphyritic varieties of Alta granodiorite.

A. Hand specimens of porphyritic granodiorite A-69-P and nonporphyritic granodiorite A-112-N.

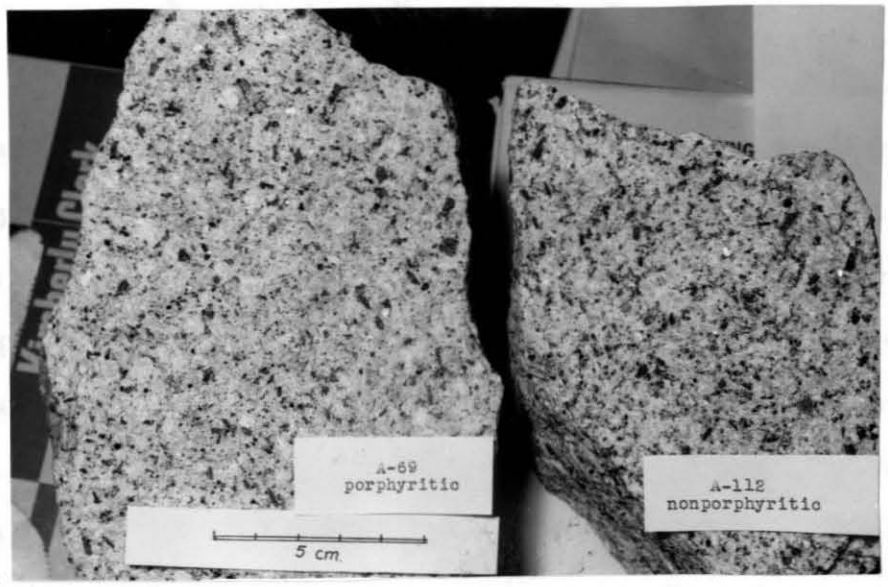
B. Photomicrograph of A-69-P, plane light, x10

C. Same as B, crossed nichols

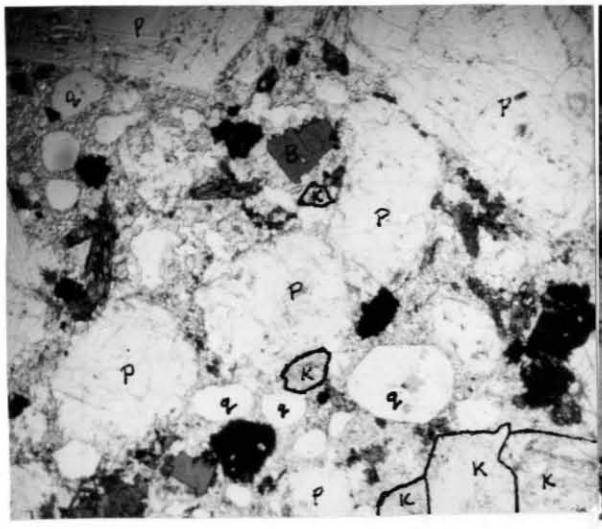
D. Photomicrograph of A-112-N, plane light, x10

E. Same as D, crossed nichols

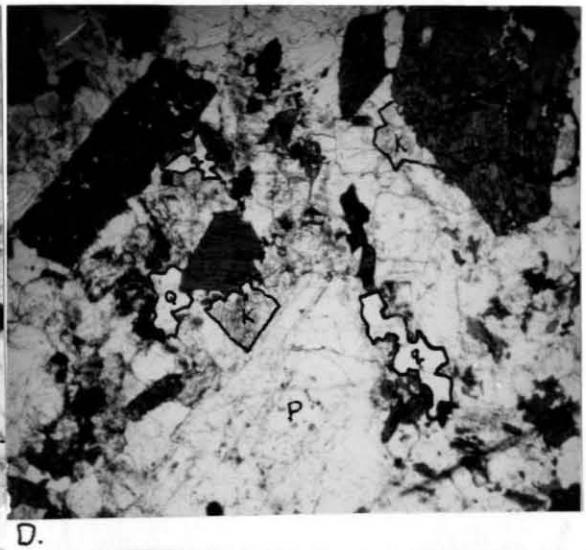
The porphyritic rock differs from the nonporphyritic rock in having a fine-grained interstitial groundmass of quartz and K-feldspar and in the presence of euhedral phenocrysts of quartz and orthoclase. Typical grains of quartz (q), orthoclase (k), hornblende (h), plagioclase (p) and biotite (b) are marked in B and D. Compare, especially, the subhedral quartz phenocrysts in B with the interstitial grains of anhedral quartz of D. The groundmass of the porphyritic granodiorite, which is best illustrated in the upper left-hand quarter of B, is composed of 49% quartz, 42% orthoclase, and 5% plagioclase, and has an average grain size of 0.05 mm. The width of the view in the photomicrographs is approximately 7 mm.



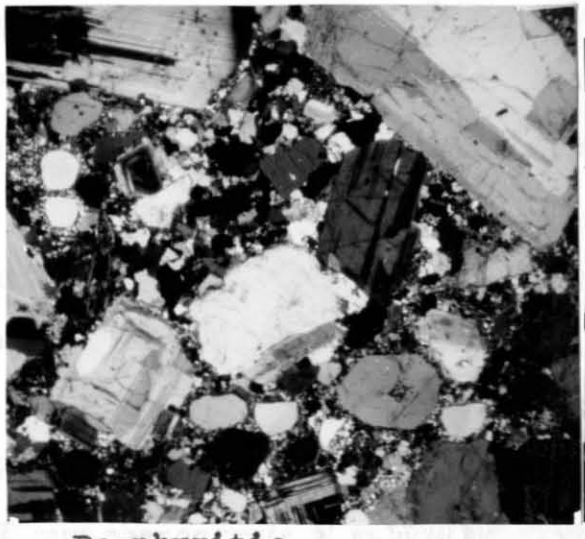
A.



B.



D.



C.

Porphyritic

E.

Nonporphyritic

Figure 2.

hornblende are the most abundant dark minerals and together make up 10 to 15 percent of the rock. Prominent black hornblende laths more than one centimeter long are present in all textural types of granodiorite and, in general, are diagnostic of rocks of the Alta stock. Brown biotite occurs as subhedral books less than three mm in maximum dimension. Sphene, chlorite and magnetite can be seen in most hand specimens but make up less than five percent of each of the textural types of the granodiorite.

Under the microscope, each of the minerals of the nonporphyritic granodiorite has a seriate grain-size distribution. Mineral grains ranging in size from 1/4 to 10 mm make up over 90 percent of the rock. Plagioclase, hornblende and biotite form crystals which have a larger average crystal size than either quartz or orthoclase.

The porphyritic rock differs from the nonporphyritic rock in having a fine-grained interstitial groundmass of quartz and K-feldspar, and in the presence of phenocrysts of euhedral quartz. The quartz phenocrysts are particularly distinctive. The groundmass makes up 20 to 35 percent of the rock. Plagioclase, hornblende and biotite make up the bulk of the phenocryst assemblage in the porphyritic granodiorite. These minerals have approximately the same grain-size distribution and general character as the corresponding minerals in the nonporphyritic granodiorite. On the other hand, quartz and orthoclase have a very different habit in the two textural types of granodiorite (compare figure 2B and 2D). In the porphyritic granodiorite these minerals occur as 1- to 2-mm phenocrysts of subhedral crystals as well as the much smaller

0.02- to 0.20-mm grains which make up the groundmass. Generally, the dark minerals are less abundant in the porphyritic rocks than in the nonporphyritic rocks. The groundmass of the porphyritic rocks is relatively free of fine-grained mafic minerals and in hand specimen it is commonly impossible to distinguish porphyritic from nonporphyritic rocks on the basis of the presence or absence of visible groundmass. On the other hand, the quartz phenocrysts of the strongly porphyritic rocks are easily observed with the hand lens and are very useful in field identification of this texture.

The location and texture of samples of granodiorite from which thin sections were cut are recorded on Plate 2.

The distribution of porphyritic and nonporphyritic granodiorites on Plate 2 is based on field observations of the size and shape of quartz grains, content of mafic minerals and spacing of joints, in addition to the thin section study. Field identifications of texture which are not supported by thin section study are not shown on Plate 2. However, these field data were useful in establishing contacts between the textural types and obtaining an idea of the homogeneity of texture between thin section localities.

The border phase of the Alta stock is characterized by a greater abundance of dark minerals and dark fine-grained inclusions and by the presence of schlieren structure. This border phase is gradational with the nonporphyritic granodiorite, and is not mapped separately on Plate 2. Generally, however, a zone containing 50 to 100 percent more mafic minerals than the average granodiorite is in contact with the wall rock. This zone commonly ranges in thickness from 50 to 200 feet. Attitude

of schlieren in the border zone are shown in Plate 3.

Fine-grained amphibolite inclusions ranging in size from one inch to several feet are found throughout the stock. These inclusions are most common near the contact but are locally abundant in the central part of the stock, such as in the porphyritic granodiorite at A-220-P about 1000 feet north of Lake Mary.

A subangular block of mafic border rock 8 feet in diameter is found in subporphyritic granodiorite, 600 feet south of Twin Lake Reservoir dam. The inclusion in turn contains abundant xenoliths of fine-grained amphibolite similar in size, color and texture to the abundant fine-grained inclusions in the border zone. No other cognate inclusions of border rock or of nonporphyritic granodiorite were noted in the Alta stock, but this could be due to their similarity in color and texture to the host rock.

Another variety of inclusions is tabular masses up to 75 feet long which are very rich in medium- to coarse-grained, euhedral biotite, hornblende and sphene, and have a pronounced planar, layered internal structure. These inclusions are called mafic layered granodiorite and are believed to be cognate. Because of their unusual character, these inclusions are discussed below under a separate heading.

The following rock types are found as dikes in the Alta stock: aplite-pegmatite, leucocratic quartz monzonite, and rhyolite. Aplite dikes, commonly with pegmatitic cores, are present in all parts of the stock, but are most abundant in the peripheral parts. Light-colored subporphyritic quartz monzonite dikes, locally containing segregations of

dark minerals, are found in the central part of the stock. With the exception of the segregations, these dikes contain less than five percent dark minerals. A rhyolite dike, 6 to 15 feet thick, crops out 300 feet east of Lake Mary and can be traced for 2000 feet along the strike north from Dog Lake. This dike is one of the "alaskite porphyry" dikes described by Calkins and Butler (1943, p. 48). The rhyolite dike is yellowish white and has a platy parting near the walls. No mafic minerals were seen in the rock and quartz is the only identifiable phenocryst. Crosscutting relations east of Lake Mary dam show that this rhyolite dike is younger than some aplite dikes.

Hornblende, sphene, epidote and pyrite are found on joint surfaces within the granodiorite and form thin, very coarse grained hornblendite veinlets. These veinlets are discussed below under a separate heading.

In the remainder of the text, thin sections are referred to by the sample locality numbers shown on Plate 2. The texture or rock type of the sample is indicated by an additional letter to the sample locality number. For example, A-112-N is a nonporphyritic granodiorite from sample location A-112. The abbreviations used in this system are

-AP aplite-pegmatite dike

-B border rock

-H hornblendite veinlet

-L leucocratic quartz monzonite dike

-ML mafic layered granodiorite

-N nonporphyritic granodiorite

-P porphyritic granodiorite

-S subporphyritic granodiorite

Nature of the Contact

The Alta stock intrudes sedimentary rocks ranging from Precambrian to Triassic in age. Paleozoic sedimentary rocks make up the wall rocks on the south, west and north sides of the stock. The Clayton Peak stock bounds the stock on the east. Dikes of the Alta granodiorite intrude the Clayton Peak diorite near the Mtn. Lake mine, south of Dog Lake. Northeast of this locality the contact between the two igneous rocks is not well exposed but limited exposures indicate that a screen of calcsilicate minerals up to 200 feet wide separates the two stocks.

The granodiorite at the contact with both sedimentary and igneous rocks is medium gray, medium grained and nonporphyritic. Dikes of this rock extend into the wall rock several feet. Commonly, the dike relations are very complex. South of Dog Lake, light-gray granodiorite dikes cut darker colored dikes of border rock and both are cut by a complex of aplite-pegmatite dikes. The granodiorite dikes are not homogeneous in character and show several distinct color changes and a few vague textural differences within an outcrop.

Although the contact of the Alta granodiorite with the rocks it intrudes is generally sharp, it is irregular in detail. Complex dike patterns and locally very abundant inclusions make the trace of the contact time consuming to follow. Little difficulty was experienced, however, in separating mafic border facies of the granodiorite from contact metamorphosed sediments.

A gradational contact of the stock was seen in only one locality. In the stream bed of Little Cottonwood Creek the south contact of the Alta stock is difficult to locate precisely because of its complexity. A broad border zone of granodiorite contains abundant large inclusions of contacted metamorphosed wall rock. As the contact is approached from within the stock the percentage of inter-xenolith granodiorite decreases. Farther into the country rock, the granodiorite forms dikes which have irregular thickness and strike. These dikes have approximately the same grain size and abundance of dark minerals as the granodiorite of the border rock. The transition from xenolith-free granodiorite to granodiorite-free country rock takes place in a distance of 200 feet.

Structural Relations Within the Stock

The nonporphyritic granodiorite generally forms a thick peripheral shell around the porphyritic granodiorite which occupies the core of the Alta stock. The porphyritic granodiorite intrudes the nonporphyritic granodiorite and the south contact generally is sharp and marked by a well-exposed, distinct selvage zone. The selvage zone consists of porphyritic rock with abundant fine-grained hornblende and biotite in the groundmass. The zone varies in thickness from a tenth of an inch to several feet, but commonly is less than two inches. The contact is very well exposed at A-307-P on the cliffs above the east shore of Lake Mary. Here, close-spaced jointing, lineation, schlieren and aplite dikes in the nonporphyritic granodiorite are cut at a large angle by the contact, whereas the lineation of the younger, porphyritic granodiorite on the

north is parallel to the contact (Fig. 3). This contact can be followed for 3000 feet from Dog Lake to the area south of Mt. Millicent. Along this length, the contact is not the trace of a curved plane, but is made up of short relatively straight segments which make sharp corners in the trace. An abrupt change in attitude of the contact is shown in Figure 3. Dip measurements on segments of the contact range from 40° to the south to nearly vertical. The effect of topography on the trace of the contact suggests a general southerly dip. Dikes of the porphyritic granodiorite can be traced for short distances into the nonporphyritic granodiorite at locations A-309-N and A-312-N east and south of Lake Mary.

From the ridge north of Mt. Millicent to the village of Brighton, the contact between the two basic textural types of granodiorite was drawn predominantly from textural information determined from thin sections and numerous hand specimens. Many short lengths of selvaged contacts were also found in this area. The longest and most continuous of these contacts, located 150 feet southeast of A-235-N (1300 feet N. 20°E. from Mt. Millicent), falls on the contact as bracketed by petrographic information. This particular segment dips 40° to the northwest and can be traced for 800 feet. Other, less continuous selvaged contacts which are approximately parallel to this one, were found north and west of A-235-N. An erosional remnant of a selvaged contact is found on a knob between A-60-S and A-61-S 1200 feet north of Mt. Millicent. This contact dips 50° to the northwest and separates subporphyritic granodiorite below from nonporphyritic granodiorite above. The contact between subporphyritic and porphyritic textured rocks which crops out at A-182-S to the

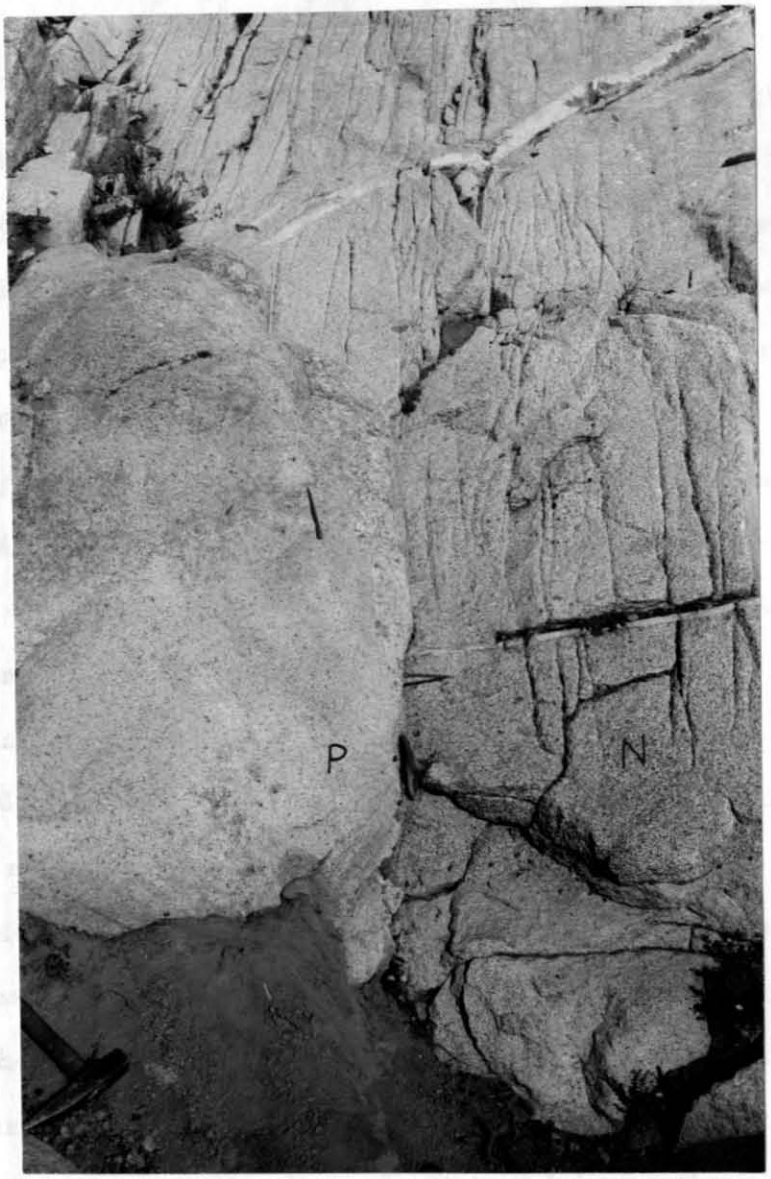


Figure 3. Contact between porphyritic granodiorite (P) and nonporphyritic granodiorite (N). Location A-307-P on the trail 700 feet south of Lake Mary dam, looking southeast. Note termination of closely spaced joints and aplite dikes in the nonporphyritic granodiorite at the contact. Orientation of lineation in the two rock types is shown by the orientation of the pencils. A thin selvage zone marks the contact in the central part of the view; dots in the lower part of the view mark the less obvious trace of the contact.

south, is at least 400 feet structurally lower than the selvage between A-60-S and A-61-S.

At A-226-P, 1000 feet north of Lake Mary, a selvaged contact with porphyritic granodiorite below and nonporphyritic granodiorite above and dipping 32° to the north occurs as an erosional remnant of the north contact of the porphyritic granodiorite (Fig. 4).

On a glaciated ridge south of Brighton and 500 feet east of location A-341-P, the contact was located within 25 feet by examination of numerous chips of bedrock under the hand lens. No selvage zone or change in jointing accompanies the change in texture of this locality. The change in texture does not coincide with a selvage zone at two other localities, 600 feet south of Mt. Millicent and between locations A-207-S and A-312-N north of Lake Martha.

Samples A-313-N, A-320-N, A-321a-N, A321b-N, and A-340-N show a nonporphyritic texture in thin section but are included within the contacts of the porphyritic granodiorite. Some of these samples may represent very large xenoliths of nonporphyritic granodiorite in the younger porphyritic granodiorite. Another origin for these rocks is suggested in the section on the origin of texture.

The eastern limit of the central mass of porphyritic granodiorite is not known. Thin sections and field observations from the poorly exposed granodiorite east of a line connecting Brighton and Dog Lake do not indicate distinctly porphyritic texture. Thin sections A-20-P, A-71-P and A-90-P from three isolated outcrops east and northeast of Brighton have strongly porphyritic texture. These outcrops may represent a

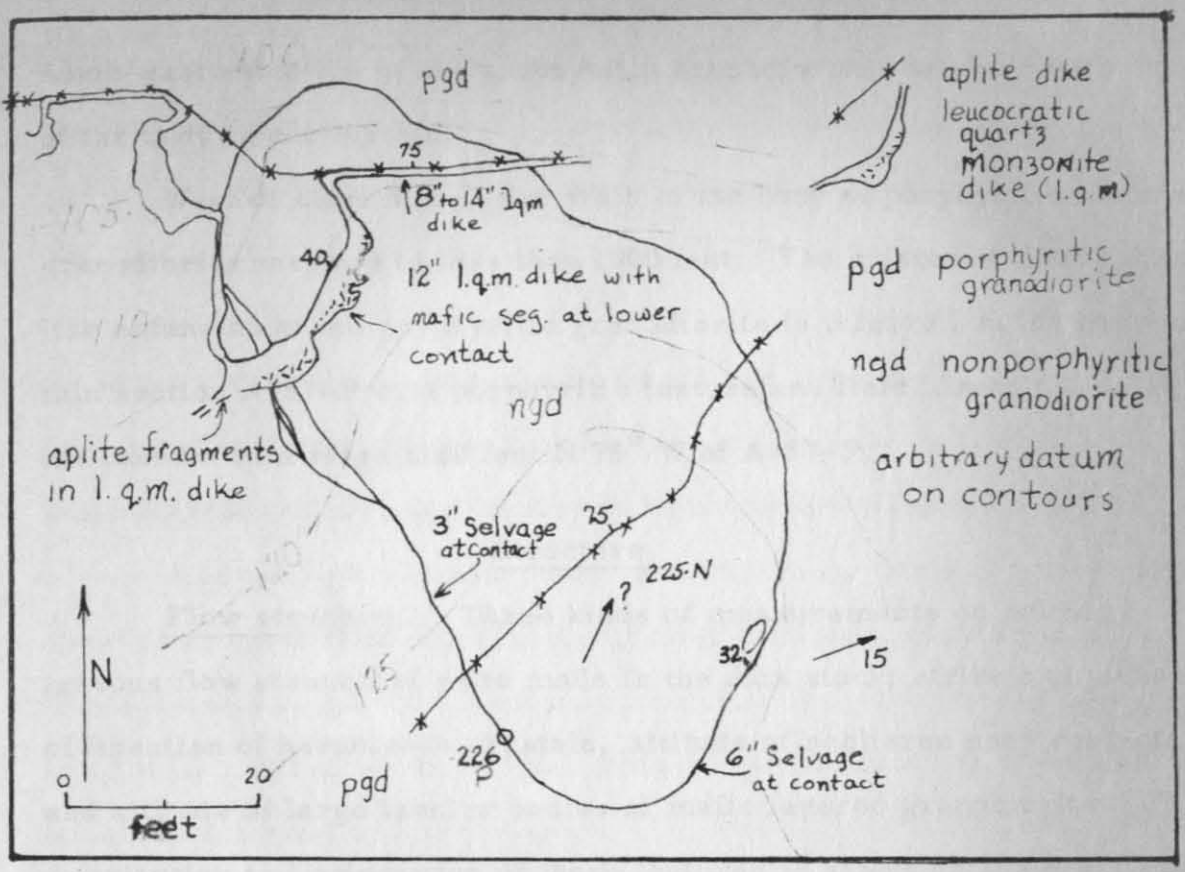


Figure 4. Sketch map of contact relations at location A-226-P, 1000 feet north of Lake Mary.

north-east extention of the porphyritic granodiorite, but the continuity of the body is not certain.

West of Lake Mary, the width of the body of porphyritic textured granodiorite narrows to less than 1000 feet. The existence of this dike-like extension of the porphyritic granodiorite is inferred on the basis of thin section A-57-P with porphyritic texture and field identification of the texture on a ridge 1300 feet N 75° W of A-57-P.

Structure

Flow structure. Three kinds of measurements on primary igneous flow structures were made in the Alta stock: strike and plunge of lineation of hornblende crystals, attitude of schlieren near contacts, and attitude of large tabular bodies of mafic layered granodiorite. The distribution and orientation of these features is shown on Plate 3. Preferred orientation of the hornblende crystals is not strongly developed and averaging several measurements at each locality is necessary, in many cases, to obtain consistent results. In some localities, a strike direction for the lineation could be obtained fairly easily, but no specific plunge could be seen. In these cases the strike direction is recorded on Plate 3 with an arrow marked by a query (?) to indicate the probable direction of dip. Such measurements may be either true lineations or intersections of foliations with outcrop surfaces.

The most common lineation trend in the stock is a westerly to southwesterly direction with plunges ranging from 15° east to 45° southwest. The porphyritic granodiorite in the vicinity of Lake Mary has a lineation which has a north-south bearing and has plunges ranging from 35° north to 45° south.

Schlieren structures in the border zone have a wide range of attitude within relatively small areas, but in general are oriented sub-parallel to the contact and dip steeply outward from the center of the stock.

Grout (Calkins and Butler 1943, p. 35) measured lineation and foliation in the Alta stock and considers "the structures to indicate an up-to-the-east movement of the magma at a moderate to low angle". The measurements shown in Plate 3 support this conclusion.

Joints. Three kinds of observations were made on joint sets in the Alta stock (Plate 4): attitude, spacing, and the presence of sulfide and silicate minerals on the joint surfaces. The attitudes on Plate 4 are the average of several measurements taken over a relatively small area and are reported to the nearest 5°, except for vertical dips which include measurements within 7° of vertical. The joint system at any one locality includes one to four joint sets. Nearly all joint sets measured have dips of more than 60°. However, at the higher elevations on Mt. Wolverine and Mt. Tuscarora, one joint set at each of several localities dips less than 60°. Information on the relative development and spacing of joints was recorded at each locality at which attitudes on joint sets were measured. Joints from 1 to 3 feet apart are called moderately spaced, those less than 1 foot are called closely spaced, and greater than 3 feet are called widely spaced. The spacing is correlative with the degree of continuity of individual surfaces in a set; thus, closely spaced joints commonly show greater continuity and generally give more consistent attitude than widely spaced joints.

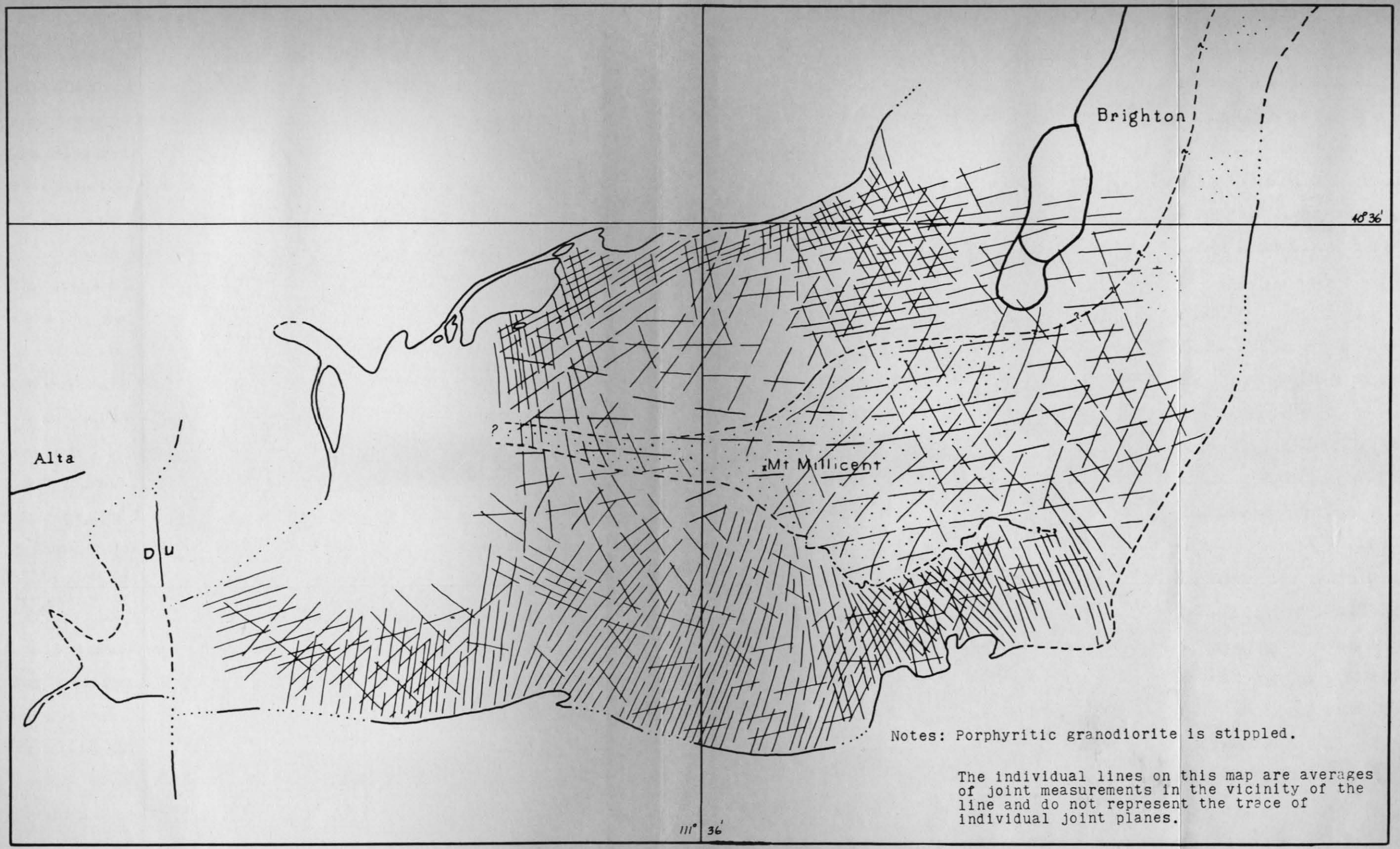
Generalizations on the strike directions recorded on Plate 4, and the qualitative information on joint spacing are presented on the interpretative map of Plate 5. The individual lines on this map are averages of joint measurements in the vicinity of the line and do not represent the trace of individual joint planes. The orientation and spacing of joints is indicated schematically on a cross section, Plate 6.

The most striking structural feature of the Alta stock is the set of closely spaced joints in the nonporphyritic granodiorite in the southern part of the stock. This set of joints is approximately perpendicular to the south contact of the Alta stock and also perpendicular to the south contact of the central mass of porphyritic granodiorite. The intrusion of porphyritic granodiorite makes its closest approach to the southern contact of the stock on the low divide between Lake Martha and Dog Lake. In this locality the nonporphyritic granodiorite has two closely spaced joint sets, which end abruptly at the southern contact of the porphyritic granodiorite (Fig. 3) and do not extend into dikes of the porphyritic rock.

There is no apparent discontinuity in joint pattern across the north contact of the porphyritic granodiorite. Closely spaced joints are found in the northern half of the stock, but they strike N. 80° E., approximately parallel to the northern contact of the stock. The distribution of these closely spaced joints has no sharp southern limit. They are well exposed on the glaciated cliffs south of Twin Lake Reservoir dam and are well developed within 250 feet of the north contact of the porphyritic granodiorite.

The porphyritic granodiorite has two prominent sets of widely spaced joints: N. 80° E. and N. 25-50° E. A third set, N. 25° W., is

PLATE 5



Notes: Porphyritic granodiorite is stippled.

The individual lines on this map are averages of joint measurements in the vicinity of the line and do not represent the trace of individual joint planes.

SCHEMATIC REPRESENTATION OF JOINT DIRECTION AND SPACING

0 2000

feet

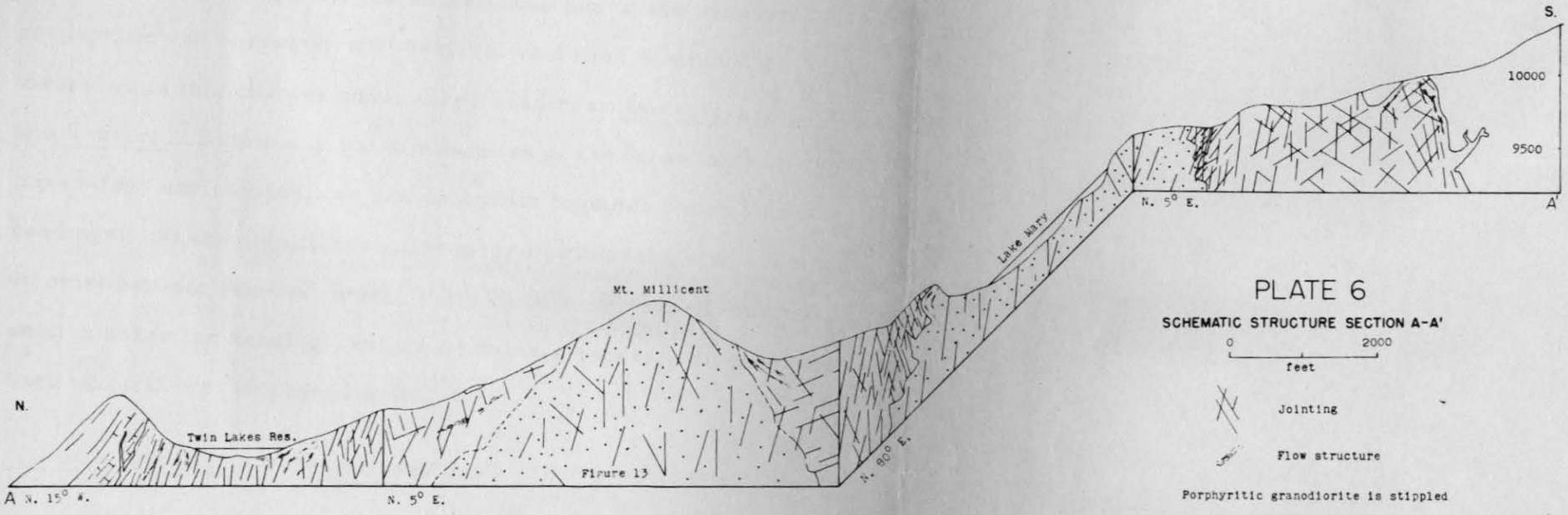


PLATE 6

SCHEMATIC STRUCTURE SECTION A-A'

0 2000

feet

Jointing

Flow structure

Porphyritic granodiorite is stippled

very poorly developed. These three joint directions are not restricted to the porphyritic granodiorite, but the wide spacing of the joints on these directions is found only in rocks having porphyritic and subporphyritic texture.

PETROGRAPHY OF THE MAJOR INTRUSIVE TYPES

The petrography of the border rock and of the porphyritic, subporphyritic and nonporphyritic textural varieties of granodiorite are discussed in this chapter under three headings: Mineralogy, Composition and Texture. Because of the similarities of the three textural types, the mineralogy and composition are described together under common headings. Where significant differences in mineralogy and composition do exist between textural types, these differences are discussed. The section under the heading Texture contains a separate discussion for each textural type of granodiorite.

Mineralogy

Plagioclase. In all textural varieties of the Alta granodiorites, plagioclase occurs in subhedral to euhedral crystals which show both oscillatory and progressive zoning (Fig. 5). The plagioclase crystals can be divided in two parts: a central part comprising approximately 85 percent of the crystal in which the composition ranges from An 30 to An 55 and averages An 37; and a thin rim comprising approximately 15 percent of the crystal in which the composition ranges from An 21 to An 26 and averages An 24. The composition of the multiple-zoned part of the plagioclase was estimated by measuring the average extinction angle in

A

B.

C.

Figure 5. Photomicrographs of zoned plagioclase crystals. Crossed nicols, x10.

A. A-69-P
B. A-309-N
C. A-3-S

crystals with favorable orientation. These data are shown in Table 5. The break in composition between the central part of the grain and the rim is generally sharp. A modal analysis of porphyritic granodiorite A-69-P in which the oligoclase rims were counted separately from the oscillatory zoned andesine core shows that 15 percent of the plagioclase phenocrysts is present as these sodic rims. In the nonporphyritic rocks, the oligoclase rims most likely comprise a greater percentage of the plagioclase abundance.

In five thin sections, traverses were made with a magnification of X450 across favorably oriented plagioclase crystals to study in detail the changes in composition which make up the oscillatory and progressive zoning. Extinction angles were measured at many points on the traverse and plotted as a function of distance from the rim of the grain (Fig. 6). Where possible the extinction angles were correlated with plagioclase composition. The details of the zoning are complex, but, in general, the composition changes from An 40 at the center of the grain to An 30 near the rim. Superimposed on this gradation are the irregularities in composition described as oscillatory zoning, which consists of narrow zones having up to 15 percent more anorthite than the intervening broader zones of less calcic plagioclase. The outline of the zones generally have the euhedral shape of plagioclase, but rounded forms are also common. The inner contact of anorthite-rich zones is commonly very sharp and embays the adjacent less calcic zone. In a short distance, these calcic zones grade outward to the next, less calcic zone.

Quartz forms myrmekitic intergrowths with the sodic rims on the plagioclase grains. These intergrowths are found only in the non-

TABLE 5. COMPOSITION OF PLAGIOCLASE IN GRANODIORITE

Sample	% anorthite		
	Central part	Rim	Remarks
A-3-S	35		
A-5-N	35		
A-58-S	43		
A-69-P phenos	37	23	44 max
A-69-P gmass	(30)		indices in the range of quartz indices
A-76-N	36	21	
A-91-B	38	25	
A-95-N	37	25	31 to 40 in main part of xl
A-135-B	37	25	30 to 39
A-137-N	39	20	55 max
A-167-P	39		45 max
A-183-P	37		
A-186-P	39		
A-219-L	42		
A-220-P	37		
A-226-P	33		
A-309-N	36		

Figure 6. Zoning in plagioclase feldspar. Extinction angles in five zoned crystals from four rocks are plotted as a function of distance in mm from the rim of the crystal. Curves are based on observations on the width and abruptness of the various zones as well as the measured and plotted points.

A. A-3-S

B. A-3-S

C. A-137-N

D. A-69-P

E. A-309-N

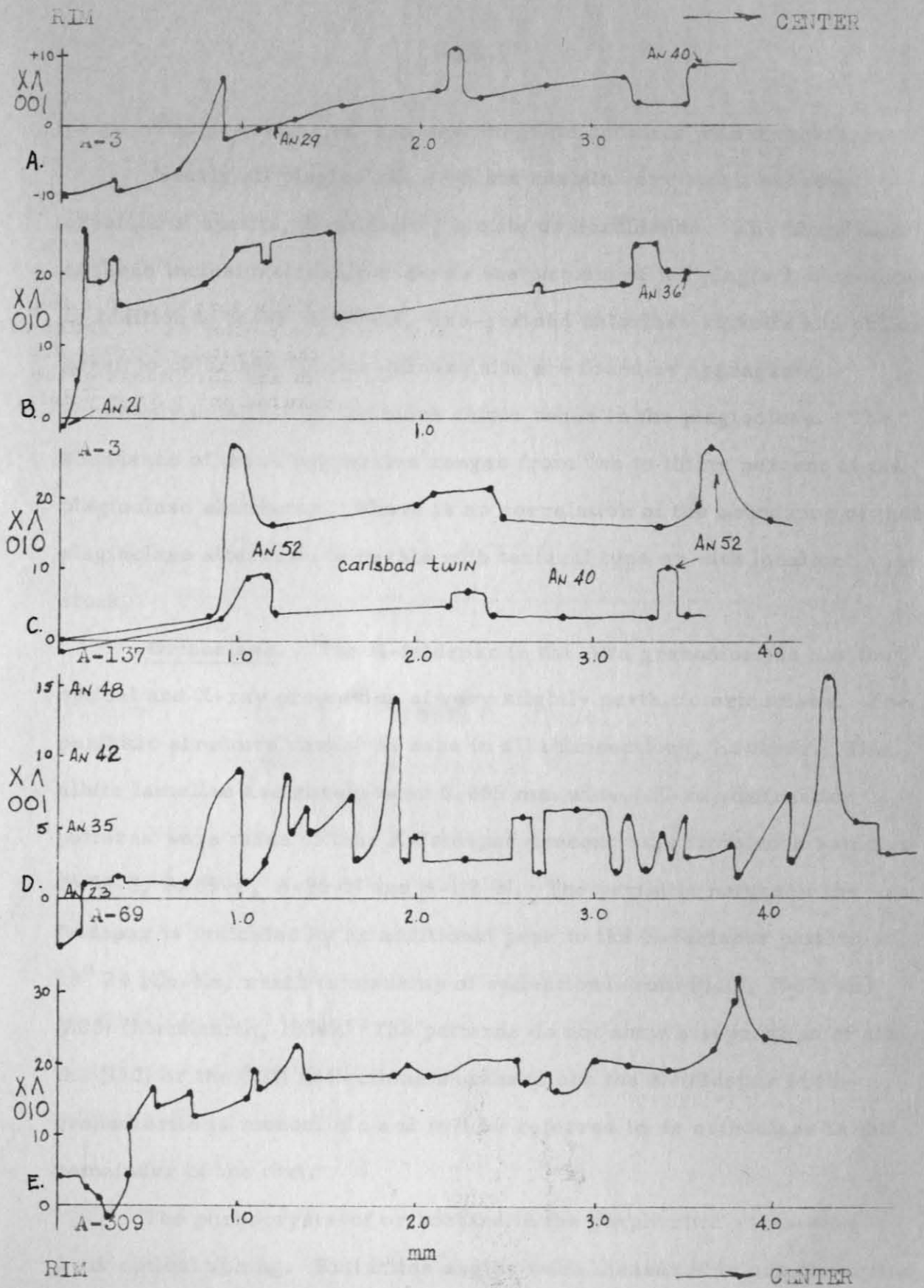


Figure 6. Zoning in plagioclase feldspar.

porphyritic granodiorite, and only on grain contacts with orthoclase.

Nearly all plagioclase crystals contain very small euhedral crystals of apatite, K-feldspar, biotite or hornblende. The abundance of these inclusions rarely exceeds one percent of the plagioclase volume. In addition to these minerals, fine-grained colorless sericite and yellow-green to colorless epidote-clinozoisite are found as aggregates, commonly localized in the more calcic zones in the plagioclase. The abundance of these aggregates ranges from two to thirty percent of the plagioclase abundance. There is no correlation of the abundance of these plagioclase alteration minerals with textural type or with location in the stock.

Orthoclase. The K-feldspar in the Alta granodiorites has the optical and X-ray properties of very slightly perthitic orthoclase. The perthitic structure cannot be seen in all thin sections, however. The albite lamellae are rarely over 0.005 mm wide. X-ray diffraction patterns were made of four K-feldspar concentrates from rock samples A-58-S, A-69-P, A-95-N and A-112-N. The perthitic nature of the feldspar is indicated by an additional peak to the K-feldspar pattern at 28° 2θ (Cu-Kα) which is made up of reflections from (040), (002) and (220) (MacKenzie, 1954). The patterns do not show a separation of either the (130) or the (131) reflections and therefore the K-feldspar in the granodiorite is monoclinic and will be referred to as orthoclase in the remainder of the text.

The phenocrysts of orthoclase in the porphyritic rocks have weak optical zoning. Extinction angles were measured in one unusually

large (10 mm) grain in A-57-P. The crystal is oriented with 010 parallel to the plane of the thin section. Using Tuttle's (1952, p. 563) correlation of extinction angle on 010 and composition, the data were expressed in terms of composition of the feldspar and plotted as a function of distance of the point of measurement from the rim of the grain. The resulting graph (Fig. 7) shows a progressive increase in

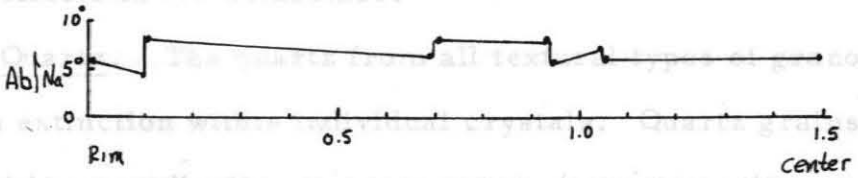


Figure 7. Zoning in orthoclase crystal from A-57-P. Extinction angles are plotted as a function of distance in mm from the rim of the crystal.

albite content toward the rim of the grain with three zones which are more sodic than the adjacent zones of feldspar. In each of the three zones, there is a gradational increase in the albite content toward the rim of the grain which is parallel to the main compositional trend in the crystal. Successive zones outward in the crystal are separated by a sharp break in composition across which there is a decrease in the albite content of the feldspar.

All orthoclase, regardless of textural variety, has a dusty appearance in thin section. This dust is concentrated in zones which in some cases radiate from inclusions or from protuberances of adjacent

minerals. Under high power the "dust" particles are irregularly shaped, and show both negative and positive relief with respect to the orthoclase. A few of the large particles contain bubbles. The smaller particles are most likely fluid-filled inclusions, although very fine grained clay is also a possibility. In addition to the dust, orthoclase contains inclusions of plagioclase, quartz, hornblende and biotite, and rarely apatite and allanite. The plagioclase inclusions are very irregular in shape. The quartz occurs as small rounded grains and small veinlets in the orthoclase.

Quartz. The quartz from all textural types of granodiorite has uniform extinction within individual crystals. Quartz grains in the non-porphyritic granodiorite, in some cases, have more than one quartz orientation and extinction angles in adjacent segments differ by more than five degrees. More than one orientation is common in phenocrysts of quartz in the porphyritic granodiorite, and in some cases the two parts of the grain are related through twinning on $(11\bar{2}2)$ with the c-axis in the two parts of the twin meeting at approximately 90°.

Quartz is relatively free of included mineral grains, but does contain two-phase fluid inclusions. These fluid inclusions are very small, 0.005 to 0.010 mm, but are very abundant. In one grain in thin section A-58-S, 75 were found in an area of 0.2 sq mm which is equivalent to 12,000 per cu mm. Although they are abundant, they make up a small part of the volume of quartz. Taking 0.004 mm as the average radius and assuming a spherical shape, the fluid inclusions form only 0.3 percent of the quartz volume in A-58-S.

Hornblende. Common green hornblende occurs as laths with typical pseudohexagonal cross section in all textural types of granodiorite. Although a euhedral outline is apparent on most crystals, the grain boundaries of the hornblende invariably show considerably embayment. In addition, the hornblende has abundant inclusions of most other minerals of the granodiorite. One typical hornblende lath from thin section A-76-N contains 5.5 percent biotite, 5.0 percent magnetite, 3.5 percent chlorite, 2.5 percent apatite, 2.0 percent zircon, 0.5 percent quartz and 0.5 percent sphene within the grain boundaries. The relative abundance of inclusions in hornblende is variable but it is generally greater than 10 percent.

A summary of optical data for hornblendes from the Alta igneous suite is found in Table 6. The pleochroic formula of the hornblendes from the major intrusive types is α = straw yellow, β = medium green and γ = dark green. No marked difference in optical properties was detected among hornblendes from the three textural types of granodiorite. However, the hornblende from the border phase, A-91-B, and the hornblende from the nonporphyritic granodiorite, A-95-P, located 600 feet south of A-91-B, both have higher indices than other hornblendes from the major intrusive types.

A hornblende concentrate from A-112-N was analyzed for major, minor and trace elements. A modal analysis of a grain thin section of this concentrate contains a total of 1.7 percent impurities. Both the original chemical analysis and the analysis corrected for impurities are found in Table 7. A structural formula was calculated from the corrected

TABLE 6. OPTICAL DATA FOR HORNBLENDE

Sample Number	Indices of Refraction ± 0.003			Optic Angle	Extinction Angle, Z∧c	Remarks
	α	β	γ			
						MAJOR INTRUSIVE TYPES
A-57-P				-70°		Porphyritic grandiorite
A-58-S	1.639	1.646	1.659			Subporphyritic granodiorite
"	1.638	--	1.659			" "
A-69-P	1.640	--	1.661	-72°		Porphyritic granodiorite
A-91-B	1.650	--	1.670		18°	Border phase
A-95-N	1.643	--	1.666	-73°	17°	Nonporphyritic granodiorite
A-112-N	1.640	1.651	1.659	-73°	19°	" "
A-322b-S	1.638	--	1.659		19°	Subporphyritic granodiorite
						OTHER TYPES
A-133				-76°		Contact metamorphosed shale
A-299-1				-69°		Amphibolite inclusion at mafic layered granodiorite locality.
A-299-3-ML	1.640	--	1.660	-73°		Coarse-grained mafic layered granodiorite
A-299-4-ML				-71°		Fine-grained mafic layered granodiorite
A-365-H				-60°		Coarse-grained amphibolite dikelet

TABLE 7. CHEMICAL ANALYSIS AND STRUCTURAL FORMULA OF THE HORNBLENDE FROM A-112-N

	1	2		3	
SiO_2	49.53	49.85			
			Z	Si 7.26	
				Al 0.71	8.00
TiO_2	1.03	0.83		P 0.03	
Al_2O_3	5.40	5.35		Al 0.21	
				Fe^{3+} 0.38	0.68
Fe_2O_3	3.46	3.52		Ti 0.09	
			Y		
FeO	9.75	9.89			
				Mg 3.21	
MnO	0.60	0.61		Fe^{2+} 1.20	4.48
				Mn 0.07	
CaO	12.45	12.19			
MgO	14.57	14.79	W	Ca 1.90	1.90
Na_2O	0.82	0.81			
			A	K 0.09	0.31
K_2O	0.52	0.48		Na 0.23	
H_2O^+	1.44	1.46			
				OH 1.42	1.42
H_2O^-	0.00	0.00			
P_2O_5	0.40	0.20			
S	negl.	negl.			
	99.97	99.98			
R_2O_3	20.99				
tot. Fe as Fe_2O_3	14.30				

column

1 D. Maynes, analyst.

2 Corrected for 1.7% impurities, determined by modal analysis of a thin section of the mineral concentrate.

3 Structural formula based on 48 cation charges in the formula $A \cdot X_2^{+2}Y_5^{+2}(Z_4^{+4}O_{11})_2(OH,F)_2$

hornblende analysis of the basis of 48 cation charges in the general amphibole formula $A\text{-}X_2Y_5(Z_4O_{11})_2(OH)_2$. A comparison of this hornblende with amphiboles of the southern California batholith is found in a later section.

Biotite and chlorite. Subhedral crystals of dark brown biotite with well-developed hexagonal basal sections are present in all phases of the Alta granodiorite. In most thin sections examined, the crystals are elongate parallel to the c-axis and have poorly-developed prismatic faces. Light-green chlorite forms partial to nearly complete pseudomorphs of the biotite.

The index of refraction, $\beta = \gamma$, for seven biotites from the Alta igneous suite are found in Table 8. The pleochroic formula of all the biotites is $\gamma = \beta$ = dark brown, α = light yellow brown. The β index of refraction in all grains measured is 1.640 ± 0.003, and the birefringence is 0.040. The biotite is optically negative with no measurable optic angle.

The indices of refraction, $\alpha = \beta$ of the chlorite in A-332b-S is 1.613. In general, chlorite from the major intrusive types of the Alta stock is pleochroic in shades of green and shows anomalous brown birefringence.

In addition to chlorite, biotite contains very small inclusions of the following minerals: sphene, magnetite, apatite, zircon, thorite and epidote. The size and abundance of apatite, zircon, and thorite inclusions is approximately the same in all thin sections studied. Chlorite, magnetite, sphene and epidote are erratic in abundance and distribution both in and between samples. Sphene and epidote occur as very small,

TABLE 8. OPTICAL DATA FOR BIOTITE

Sample Number	Indices of Refraction $\beta = \gamma$ ± 0.003	Rock type
A-58-S	1.642	Subporphyritic granodiorite
A-69-P	1.642	Porphyritic granodiorite
A-91-B	1.646	Border phase
A-95-N	1.642	Nonporphyritic granodiorite
A-112-N	1.642	Nonporphyritic granodiorite
A-299-3-ML	1.640	Mafic layered granodiorite
A-322b-N	1.638	Porphyritic granodiorite

TABLE 9. FLUORINE IN BIOTITE

Sample Number	% F	Rock type
A-69-P	0.73 ± 0.10	Porphyritic granodiorite
A-102-AP	1.28 ± 0.22	1 cm xl in Albion Basin pegmatite
A-112-N	0.85 ± 0.14	Nonporphyritic granodiorite

high relief grains in the chlorite. Magnetite is found as small euhedral crystals concentrated on the periphery of the biotite grains. One biotite grain in thin section A-76-N which contains no chlorite, contains 4.0 percent apatite, 0.3 percent zircon and 0.4 percent magnetite.

A chemical analysis of a biotite concentrate from A-112-N is found in Table 10. Spectrographic analyses for fluorine in this biotite and two others from the Alta igneous suite are found in Table 9. The biotite concentrate from A-112-N contains 0.5 percent sphene, 1.8 percent hornblende, and 2.8 percent chlorite. The chemical analysis, corrected for these impurities and equated to 100 percent, is given in column 2 of Table 10. A structural formula was calculated from the corrected analysis on the basis of 22 cation charges in the phlogopite formula $KMg_3Al\ Si_3O_{10}(OH)_2$. The structural formula is unusual in that all the Al is required in the tetrahedral site and that the octahedral site is filled to capacity. A 10 percent deficiency is present in the large cation position.

Comparison with the biotite and amphibole of the southern California batholith. Larsen and Draisin (1950) report chemical analysis of 8 biotites and 11 amphiboles from chemically analyzed rocks of the southern California batholith. These mafic minerals come from a suite of rocks which ranges in composition from gabbro to leucogranite. Unfortunately, no minerals were analyzed from granodiorite with a quartz-orthoclase ratio as low as that in the granodiorite of the Alta stock.

The hornblende and biotite from the batholith appear to have FeO and MgO contents systematically related to the composition of the parent rock. As plotted against $1/3\ SiO_2 + K_2O - CaO - MgO - FeO$ in

TABLE 10. CHEMICAL ANALYSIS AND STRUCTURAL FORMULA OF THE BIOTITE FROM A-112-N

	1	2	3		
SiO_2	37.37	37.36	Si	2.77	
			Al	1.21	3.99
TiO_2	3.35	3.26	P	0.01	
Al_2O_3	13.78	13.90			
			Al	none	
Fe_2O_3	3.28	3.40	Fe^{3+}	0.19	
			Mn	0.03	2.97
FeO	14.28	14.78	Mg	1.45	
			Fe^{2+}	0.92	
MnO	0.45	0.46	Ti	0.18	
			Li	0.20	
CaO	0.86	0.46			
MgO	13.42	13.13	Ca	0.04	
			Na	0.02	0.91
Na_2O	0.17	0.17	K	0.82	
			Rb	0.03	
K_2O	8.27	8.72			
H_2O^+	2.70	2.44	OH	1.19	1.44
			F	0.21	
H_2O^-	0.08	--			
P_2O_5	0.11	0.11			
S	negl.	negl.			
F	0.85[a]	0.90			
Li_2O	0.65[a]	0.70			
Rb_2O	0.75[a]	0.65			
	100.37	100.44			
O = F	0.36	0.38			
	100.01	100.06			
R_2O_3	36.85				
total Fe as Fe_2O_3	19.36				

a) Analyzed spectrographically by E. Godijn.

1. D. Maynes, analyst.
2. Corrected for impurities, determined by modal analysis of thin section of grain mount.
3. Structural formula based on 22 cation charges in the general biotite formula $K(Mg, Fe)_3(AlSi_3O_{10})(OH, F)_2$

$\beta = \gamma = 1.642 \pm 0.003$

c = 10.10 Å (Si internal standard)

the rock, FeO in the constituent hornblendes and biotites increases whereas MgO decreases. Granodiorites with the same 1/3 SiO_2 + K_2O - CaO - MgO - FeO as the granodiorite of the Alta stock should contain biotite with 18 percent FeO and 10 percent MgO. Both the hornblende and the biotite of the Alta stock, however, have compositions more comparable to hornblende and biotite respectively from hornblende gabbros of the southern California batholith. In addition, the hornblende of A-112-N contains less Al_2O_3 and more SiO_2 than any of the 11 analyzed hornblendes of the southern California batholith.

Accessory minerals. The common accessory minerals in the granodiorite are magnetite, sphene and apatite. Zircon, allanite, epidote, thorite (?), pyrite and hematite are also found in the granodiorite but the maximum abundance of each is only a few tenths of one percent.

Magnetite occurs predominantly as inclusions in hornblende and biotite, but also as individual crystals between grains of the major minerals, as a component of the groundmass of the porphyritic granodiorite, and as aggregates of individual subhedral crystals. In all cases, magnetite forms euhedral to subhedral crystals which range in size from 0.06 mm to 0.5 mm. The magnetite appears homogeneous in reflected light on polished surfaces. Magnetite is the only opaque mineral found in all thin sections of Alta granodiorite studied except A-137-N which contains 0.2 percent euhedral pyrite with rims of hematite.

Sphene forms characteristic yellow-brown, euhedral wedge-shaped crystals in all textural varieties of the granodiorite. Inclusions of apatite and magnetite are common in the sphene. Anhedral, very small grains of sphene are found in chlorite, probably as an alteration

byproduct of biotite.

Apatite forms 0.01 mm to 0.5 mm euhedral prismatic crystals and is most common as inclusions in biotite and hornblende. The indices of refraction of the apatite from A-69-P are approximately $\varepsilon = 1.632$ and $\omega = 1.636$. The apatite is zoned with successive zones differing in index of refraction by as much as 0.005.

Allanite occurs as rare, 0.5- to 2.0-mm subhedral, lath-shaped crystals, which have strong, red to brown pleochroism.

Zircon and thorite (?) are very rare and form very small crystals. Bipyramidal crystals of zircon occur most commonly as inclusions in biotite but these inclusions do not have a pleochroic halo. Slightly larger anhedral, high birefringent grains which do have pleochroic halos in biotite are tentatively called thorite.

Composition of the Major Intrusive Types

Modal composition. Variations in mineral composition among the major intrusive rock types were investigated with 29 point-count modal analyses of the least altered rocks in the Alta stock. The modal analyses were made under 100x magnification using an average of 1700 points on eight sq cm of area in each rock slice. Most of the thin sections, especially those of the finer grained rocks, were etched with hydrofluoric acid and treated with sodium cobaltinitrite to stain the K-feldspar yellow, etch the plagioclase and leave the quartz relatively unaffected. Plagioclase alteration minerals were counted as a group and distinguished from unaltered plagioclase. Individual alteration minerals were not counted separately. The chlorite abundances include a small amount of very fine grained sphene and epidote.

TABLE 11. MODAL ANALYSES OF NONPORPHYRITIC GRANODIORITE FROM THE ALTA STOCK

volume %

	A-7	A-14	A-76	A-95a	A-95b	A-112-1	A-112b	A-137	A-309	A-313	Average
Plagioclase	28.6	40.4	36.6	45.5	39.2	45.65	44.4	45.2	47.8	44.3	40.7
Plag alt min	12.3	2.3	4.2	0.9	2.7	2.7	2.8	7.5	1.3	4.7	5.15 ± 3.0
Orthoclase	22.0	21.7	22.4	20.7	18.9	15.8	18.1	16.3	18.7	16.4	19.1 ± 2.1
Quartz	17.4	15.6	22.2	18.8	19.6	19.65	22.4	17.6	20.2	23.1	19.6 ± 1.9
Hornblende	11.2	11.3	4.2	5.4	4.0	7.4	4.7	4.8	3.1	3.4	6.0 ± 2.4
Biotite	1.8	5.2	6.9	5.7	8.95	6.3	5.9	5.1	6.3	3.8	5.6 ± 1.4
Magnetite	1.4	2.1	0.9	1.7	4.4	1.0	0.8	0.9	1.2	1.6	1.6 ± 0.6
Apatite	0.6	0.3	0.7	0.7	0.8	0.35	0.2	0.4	0.3	0.4	0.5 ± 0.2
Sphene	2.1	0.6	0.7	0.2	0.4	0.35	0.4	0.8	0.4	0.3	0.6 ± 0.4
Chlorite	2.7	0.5	1.1	0.2	1.0	0.8	0.3	1.1	0.4	1.6	1.0 ± 0.5
Zircon	---	0.2	0.2	---	0.05	0.05	---	---	0.05	0.2	
Allanite	---	---	---	---	---	---	---	---	---	---	
Epidote	---	---	---	---	---	---	---	---	---	---	
Pyrite	---	---	---	---	---	---	---	0.1	---	---	
Hematite	---	---	---	---	---	---	---	0.1	---	---	
Unknown	---	---	---	---	---	0.1	---	---	---	---	
Total	100.1	100.2	100.1	99.8	100.00	100.05	100.0	99.9	99.75	99.9	100.00
Counted	1613	1707	1737	1633	1859	3316	1725	1663	1866	1830	
K in plag.	---	---	0.3	0.3	0.3	---	---	0.1	---	---	
B in H	---	---	0.2	0.2	0.1	0.3	---	0.2	0.1	---	
B in plag.	---	---	0.1	0.1	0.05	---	---	0.1	---	---	
S in chl	---	---	---	---	---	0.2	---	---	0.1	0.5	
Myrmekite	---	---	---	0.6	0.4	---	---	---	---	---	
B + C	4.5	5.7	8.0	5.9	9.95	6.85	6.2	6.2	6.6	4.9	5.6 ± 1.1
Color index	19.0	20.2	14.0	13.8	18.75	15.8	12.1	12.9	11.5	11.4	13.9 --
Total plag.	40.9	42.7	40.8	46.1	41.7	48.35	47.2	52.7	49.1	42.0	45.85 ± 3.5
Other	---	0.2	0.2	0.1	0.05	0.15	---	0.2	0.1	0.3	0.15 ± 0.15

TABLE 11 (Continued)

ABBREVIATIONS USED IN TABLES 11 TO 16

Plag alt min	plagioclase alteration minerals
K in plag.	orthoclase included in plagioclase
B in H	biotite in hornblende
S in chl	sphene in chlorite
B + C	sum of biotite and chlorite abundance
B in plag.	biotite in plagioclase
Total plag.	plagioclase + plagioclase alteration minerals

TABLE 12. MODAL ANALYSES OF PORPHYRITIC GRANODIORITE FROM THE ALTA STOCK

volume %

	A-69	A-176	A-183	A-186	A-220	A-224	A-226	A-307	Average
Plagioclase	44.75	} 50.3	} 41.6	45.1	} 53.9	45.0	} 52.7	38.1	} 48.6
Plag alt min	1.3			6.6		3.8		6.0	
Orthoclase	18.1	22.8	20.6	18.2	17.3	19.2	16.8	15.5	18.55 ± 1.7
Quartz	21.1	18.3	27.1	17.9	18.0	21.3	18.3	27.1	21.2 ± 2.6
Hornblende	4.15	2.8	2.1	3.4	3.0	3.6	4.6	1.1	3.05 ± 0.8
Biotite	6.7	3.8	1.0	4.4	5.3	3.1	3.5	2.3	3.75 ± 1.4
Magnetite	1.4	0.9	1.1	1.4	1.2	1.4	1.2	0.6	1.15 ± 0.2
Apatite	0.25	0.4	0.4	0.5	0.2	0.2	0.4	0.5	0.35 ± 0.2
Sphene	0.7	0.4	0.4	0.6	0.6	0.5	0.2	0.4	0.5 ± 0.1
Chlorite	1.4	0.4	5.5	1.8	0.4	1.8	2.4	7.2	2.6 ± 1.8
Zircon	0.15	0.1	---	0.1	---	---	0.1	0.1	
Allanite	0.05	---	---	---	---	---	---	0.4	
Epidote	---	---	---	---	---	---	---	0.05	
Biotite 2	---	---	---	---	---	---	---	0.35	0.2
Lucoxene	---	---	---	---	---	---	---	0.35	
Hematite	---	---	---	---	---	---	---	0.15	
Total	100.05	100.2	99.8	100.0	99.9	99.9	100.2	100.2	99.85
Count	3319	1624	1586	1612	1606	1599	1614	1910	1860
Phenocrysts									
Plagioclase	42.25	48.2	38.1	44.0	52.8	43.8	48.8	35.8	46.2
Orthoclase	3.3	5.7	3.8	7.0	5.9	7.0	1.2	4.5	4.8
Quartz	8.7	8.6	12.2	11.4	8.6	10.3	4.0	11.3	9.4
Groundmass	29.7	30.0	35.1	20.2	23.1	24.1	33.8	36.6	27.85 ± 5.3
Plagioclase	2.5	2.1	3.5	1.1	1.1	1.2	3.9	2.3	2.4
K-feldspar	14.8	17.1	16.8	11.2	11.4	11.9	15.6	11.0	13.7
Quartz	12.4	9.7	14.9	6.5	9.4	11.0	14.3	15.8	11.75
K in plag.	0.3	---	---	---	---	0.3	---	---	
B in H	0.1	---	---	---	---	---	---	---	
B in plag.	---	---	---	---	---	---	---	---	
S in chl	0.9	---	---	---	---	---	---	1.9	
B + C	7.65	4.2	6.6	6.2	5.7	5.1	5.9	7.6	6.35 ± 0.9
Color index	14.55	8.4	9.1	11.7	10.5	10.4	11.9	12.9	11.25
Total plag.	46.05	50.3	41.6	51.7	53.9	48.8	52.7	44.1	48.65 ± 3.5
Other	0.2	0.1	---	0.1	---	---	0.1	1.25	0.2

TABLE 13. MODAL ANALYSES OF SUBPORPHYRITIC GRANODIORITE FROM THE ALTA STOCK

volume %

	A-3	A-45	A-58a	A-58b	A-212	Average
Plagioclase	38.2	42.7	38.7	44.7	} 52.0	} 48.1 ± 1.5
Plag alt min	8.3	3.7	9.2	3.2		
Orthoclase	17.9	17.4	14.9	17.2	16.3	16.7 ± 0.8
Quartz	17.8	21.2	21.6	20.1	17.9	19.7 ± 1.5
Hornblende	9.9	4.4	4.1	3.4	5.4	5.4 ± 1.7
Biotite	3.4	6.8	7.4	7.5	3.2	5.65 ± 1.8
Magnetite	1.6	1.4	1.1	1.4	1.55	1.4 ± 0.1
Apatite	0.2	0.8	0.6	0.7	0.4	0.5 ± 0.2
Sphene	0.8	0.8	0.7	0.6	0.3	0.65 ± 0.15
Chlorite	2.0	0.7	1.1	1.0	2.7	1.5 ± 0.7
Zircon	---	0.05	---	0.1	0.05	
Allanite	---	---	---	---	0.05	
Epidote	---	---	0.3	---	---	0.2
Hematite	---	---	0.2	---	---	
Unknown	---	---	0.2	---	---	
Total	100.1	99.95	100.1	99.9	99.85	99.8
Count	1767	1805	1947	1727	3204	
Phenocrysts						
Plagioclase	---	---	---	---	49.45	
Orthoclase	5.4	---	---	1.75	3.1	
Quartz	5.1	---	---	7.6	5.6	
Groundmass						
Plagioclase	---	---	---	---	2.55	
K-feldspar	---	---	---	---	13.2	
Quartz	---	---	---	---	2.3	
K in plag.	---	0.2	0.35	0.3	---	
B in plag.	---	---	0.05	0.1	---	
B in H	---	---	---	1.3	---	
S in chl	---	---	---	---	---	
B + C	5.4	7.5	8.5	8.5	5.95	7.1 ± 1.0
Color index	17.9	14.2	15.2	13.9	13.6	
Total plag.	46.5	46.4	47.9	47.9	52.0	48.1 ± 1.5
Other	---	0.1	0.7	0.1	0.1	0.2

TABLE 14. MODAL ANALYSES OF BORDER ROCKS OF THE ALTA STOCK

volume %

	A-5	A-91	A-135	Average	
Plagioclase	47.3	56.3	52.8	52.1	
Plag alt min	11.0	6.9	3.6	7.2	
Orthoclase	5.7	3.2	7.2	5.3	± 1.1
Quartz	5.9	13.0	8.5	9.1	± 2.6
Hornblende	14.1	9.9	12.8	12.3	± 1.6
Biotite	8.0	5.9	11.5	8.5	± 2.0
Magnetite	2.7	2.2	1.6	2.2	± 0.4
Apatite	1.1	0.5	0.7	0.8	± 0.2
Sphene	1.4	0.2	0.5	0.7	± 0.5
Chlorite	2.9	1.8	0.5	1.7	± 0.8
Zircon	---	---	0.2		
Allanite	---	0.1	---	0.2	
Epidote	---	0.8	---		
Total	100.1	100.2	99.9	100.1	
Count	1464	1660	1763	1630	
Ortho in plag.	---	---	0.3		
B in plag.	---	---	0.1		
B in H	---	---	0.6		
S in chl	---	0.6	---		
Myomekite	---	0.2	0.2		
B + C	10.9	7.9	12.0	10.2	± 1.8
Color index	29.1	21.2	26.9	25.6	
Total plag.	57.6	63.1	56.4	59.0	± 2.7
Other	---	0.3	0.2	0.2	
Distance from contact (feet)	50	100	150		

TABLE 15. MISCELLANEOUS MODAL ANALYSES OF SAMPLES COLLECTED IN THE ALTA STOCK

volume %

	A-63	A-81	A-133	A-219	A-78	A-108
Plagioclase	47.8	49.2	47.6	41.6	} 48.0	} 5.3
Plag alt min	2.7	2.0	2.7	3.7		
Orthoclase	17.3	15.5	4.4	25.2	19.5	64.9
Quartz	19.7	9.6	7.9	17.9	23.0	30.0
Hornblende	4.6	12.1	25.3	2.2	2.5	---
Biotite	6.5	7.2	9.8	5.0	3.0	0.1
Magnetite	0.7	1.9	0.7	1.4	1.0	---
Apatite	0.1	0.9	0.5	0.5	0.5	0.2
Sphene	0.3	1.5	0.1	0.5	---	---
Chlorite	0.3	0.6	1.0	1.9	3.0	0.7
Zircon	---	---	0.1	---	---	---
Calcite	---	---	0.1	---	---	---
Muscovite	---	---	---	---	---	0.5
Hematite	---	---	---	---	---	0.05
Unknown	---	---	---	---	---	0.1
Total	100.0	99.8	100.1	99.9	99.5	100.05
Count	1715	1851	1651	1667	492	3018
K in plag.	0.3	0.3	0.2	0.1	---	---
Myrmekite	---	---	---	---	---	0.5
B in H	0.1	---	2.3	---	---	---
B in plag.	---	---	0.2	---	---	---
H in plag.	---	---	0.1	---	---	---
B + C	6.8	7.8	10.8	6.9	6.0	0.8
Color index	12.4	23.3	36.9	11.0	9.5	0.8
Total plag.	50.5	51.2	50.3	45.3	48.0	5.3

Sample	Rock type
A-63	Nonporphyritic granodiorite within central mass of porphyritic granodiorite.
A-81	Border phase of the Alta stock in the Scotts Pass area.
A-133	Amphibolite, contact metamorphosed shale from the Mineral Fork tillite (Precambrian).
A-219b	Porphyritic granodiorite host for leucocratic quartz monzonite dike A-219a.
A-78	Strongly porphyritic granodiorite.
A-108	Potassic aplite from dike connected to the upper surface of the Albion Basin pegmatite.

The modal analyses, grouped according to textural and compositional type, are found in Tables 11 to 15. These data are in volume percent and subsequent use of the modes is on this basis unless stated otherwise. Each column in the tables represents a single analysis of one thin section except in the case of A-112-N in Table 11 and A-69-P in Table 12, which are the average of modes of two thin sections from the same hand specimen from each of these two localities.

The average modal composition of each of the major intrusive types is found in Table 16. No attempt was made to test variations in composition within hand specimens or outcrops. The averages shown in columns 1 to 4 of Table 16 are simple unweighted averages of the modal analyses shown in Tables 11, 12, 13 and 14. Column 3 is the average of all modes from nonporphyritic granodiorite except three which are of samples collected near the contact. These three, representing the border phase of the nonporphyritic granodiorite, are averaged separately in column 4. For comparison, the average composition of the mafic layered granodiorite (to be discussed later) is given in column 5.

Two types of alteration are found in the Alta stock: chloritization of biotite and sericitization of plagioclase. Fine-grained sphene and epidote accompany the chlorite alteration. Clay minerals and a mineral in the clinozoisite-epidote group are found with sericite in plagioclase. Hornblende may also have been altered to chlorite, but commonly the chlorite in hornblende appears to be pseudomorphic after biotite. The maximum measured abundance of plagioclase alteration minerals is

TABLE 16. AVERAGE PREALTERATION MODAL COMPOSITION OF MAJOR INTRUSIVE TYPES

volume %

	1	2	3	4	5	6	7
Total plag.	48.65	48.1	45.85	59.3	27.4	66.1	8.5
Orthoclase	18.55	16.7	19.1	5.3	12.1	6.9	49
Quartz	21.2	19.7	19.6	9.1	12.0	13.5	42.5
Hornblende	3.05	5.4	6.0	12.3	21.5	4.4	(a)
B + C	6.35	7.1	6.6	10.2	17.5	9.1	(a)
Magnetite	1.15	1.4	1.6	2.2	5.6		
Apatite	0.35	0.5	0.5	0.8	1.1		
Sphene	0.5	0.65	0.6	0.7	2.4		
Other	0.2	0.2	0.15	0.2	0.3		
Total	99.85	99.8	100.0	100.1	99.9	100.0	100.0
Color index	11.25	13.6	13.9	25.6	47.3	13.5	
K/TP+K	0.28	0.26	0.30	0.08	0.30	0.09	0.85
B+C/B+C+H	0.69	0.57	0.52	0.45	0.45		
Q/K	1.14	1.18	1.03	1.7	1.0	1.95	0.87

K/TP + K is Orthoclase/Total plagioclase + orthoclase

B+C/B+C+H is biotite+chlorite/biotite+chlorite+hornblende

Q/K is Quartz/orthoclase

Column

1 Porphyritic granodiorite, Table 12.

2 Subporphyritic granodiorite, Table 13.

3 Nonporphyritic granodiorite, Table 11.

4 Border rock, Table 14.

5 Mafic layered granodiorite, Table 23.

6 Phenocryst assemblage of porphyritic granodiorite, Table 12.

7 Groundmass of porphyritic granodiorite, Table 12.

12.3 percent in A-7-N, which is approximately one-third the volume of total plagioclase in this rock. In A-183-P, nearly all of the biotite has been altered to chlorite, epidote and sphene. Only a few of the 150 thin sections studied have less than 2 percent plagioclase alterations minerals or less than 0.5 percent chlorite.

Because the modes were made on the least altered and least weathered rocks seen in thin section, the average modes are not representative of the present composition of the Alta granodiorite. Therefore it is more meaningful to discuss the data in terms of the rock's pre-alteration modal composition.

Examination of the modes in Tables 9 to 12 shows that the abundance of chlorite and of the group of plagioclase alteration minerals varies widely within each rock type. The sum of the average abundances of unaltered plagioclase and plagioclase alteration minerals is shown in Table 16 as total plagioclase, and is probably a reasonable estimate of the pre-alteration abundance (in volume percent) of plagioclase. Similarly, the sum of the average abundances of biotite and chlorite for each rock type as shown in the table is useful in comparing the average pre-alteration abundance (in volume percent) of biotite of the major intrusive rock types.

The tabulation used in the average modes differs from that used in the original data in two other respects; textural varieties of the minerals are not reported separately and the minor accessory minerals are lumped together under the heading Other.

The relative deviation of the means associated with the modal

averages (in percent of the average value) ranges from 5 percent to 11 percent for plagioclase, quartz and orthoclase; from 25 percent to 40 percent for hornblende and biotite; but only 14 to 17 percent for biotite-chlorite.

In order to study compositional trends which may exist between the major intrusive types the following parameters were calculated for the averages shown in Table 16: 1) the color index, which is equal to the sum of the abundances of the dark minerals in volume percent; 2) the prealteration feldspar ratio, total plagioclase/total plagioclase + orthoclase; 3) the quartz-orthoclase ratio; and 4) the prealteration ratio of major mafic minerals, biotite + chlorite/biotite + chlorite + hornblende.

On the basis of the modal data, the major intrusive types of the Alta stock can be listed in the following order of increasing silicic composition: (1) border rock (least silicic), (2) nonporphyritic granodiorite, (3) subporphyritic granodiorite, and (4) porphyritic granodiorite (most silicic). This is the order in which the color index and the abundances of hornblende, magnetite, apatite and sphene decrease; and it is also the order of increasing quartz content and the order in which the pre-alteration biotite-hornblende ratio (biotite + chlorite/biotite + chlorite + hornblende) increases. In this sequence the largest difference in composition occurs between the border rock and the nonporphyritic granodiorite. The average nonporphyritic granodiorite has only one half the color index but over twice the quartz and orthoclase that the border rock contains.

Although the deviation of the measurements is large relative to the differences in composition between the three textural types of grano-

diorite, the following generalizations are probably valid. The porphyritic granodiorite is a more leucocratic rock and contains more quartz and plagioclase then the nonporphyritic granodiorite. Exclusive of the border rock, hornblende and perhaps magnetite, sphene and apatite are most abundant in the nonporphyritic granodiorite.

The average composition of the major intrusive types is plotted in terms of quartz, orthoclase and total plagioclase abundances on the ternary diagram in Figure 8. Because the major minerals of the porphyritic granodiorite are not distributed equally between the groundmass and the phenocrysts, the composition of the phenocrysts assemblage of each of the modes of the porphyritic rocks is also shown in Figure 8. Tie lines connect mineral composition of the phenocrysts with the corresponding composition of the rock. The average composition of the groundmass of the porphyritic granodiorites is shown at point G.

The average composition of the phenocryst assemblage is close to the average composition of the border rock. The felsic mineral ratios and the abundance of biotite + chlorite are similar in the two averages (compare columns 4 and 6 of Table 16 and position of points Ph and B, Figure 8) but are decidedly different from these parameters in the three textural varieties of granodiorite. The border rock, however, contains 7 volume percent more total plagioclase and 9 volume percent more dark minerals than the average composition of the phenocryst assemblage of the porphyritic rock.

Chemical composition. Chemical analyses were obtained of two of the least altered and least weathered rocks in the Alta stock (Table 17).

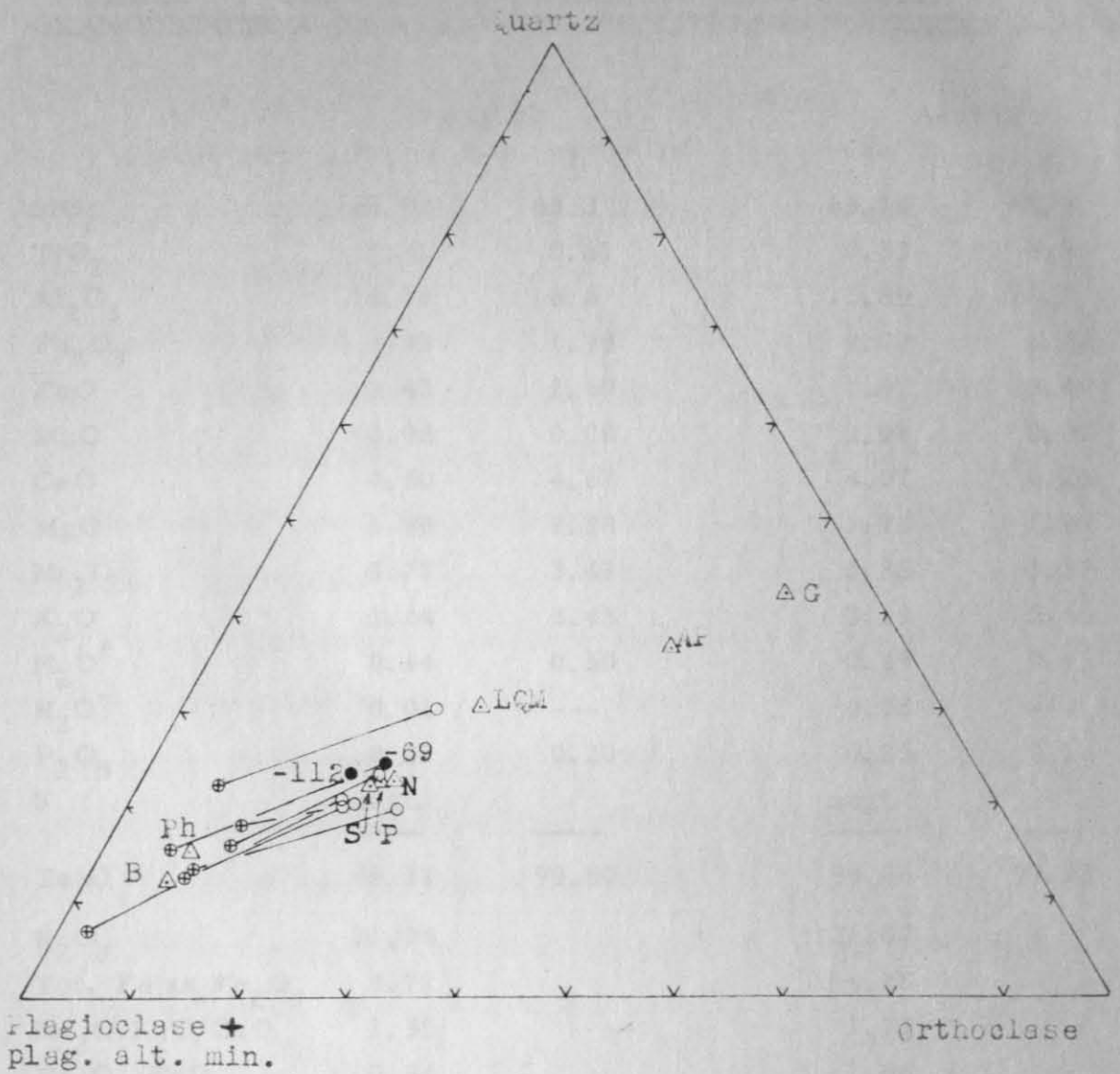


Figure 8. Ternary plot of quartz, orthoclase and total plagioclase modal abundances in the Alta igneous suite. Average composition (△) of border rock (B), nonporphyritic granodiorite (N), porphyritic granodiorite (P), subporphyritic granodiorite (S), leucocratic quartz monzonite dikes (LQM), aplite-pegmatite dikes (AP) and the groundmass of the porphyritic granodiorite (G) are plotted. Phenocryst composition (⊕) and total rock composition (o) are shown for modes of porphyritic rocks. The compositions of the rocks used in the chemical analyses, A-69-P and A-112-N are also plotted. The average composition of the phenocryst assemblage is shown at point Ph.

TABLE 17. CHEMICAL COMPOSITION OF NONPORPHYRITIC GRANODIORITE A-112-N AND PORPHYRITIC GRANODIORITE A-69-P

	A-112-N		A-69-P	
	1	2	3	4
SiO_2	63.92	63.3	63.70	63.8
TiO_2	0.61	0.61	0.53	0.90
Al_2O_3	16.13	16.6	15.89	16.1
Fe_2O_3	2.03	1.99	2.09	2.24
FeO	2.43	2.60	1.97	2.49
MnO	0.08	0.08	0.07	0.07
CaO	4.50	4.67	4.07	4.28
MgO	1.90	2.38	1.73	1.99
Na_2O	3.77	3.43	3.85	3.37
K_2O	3.24	3.45	3.19	3.66
H_2O^+	0.44	0.50	0.49	0.46
H_2O^-	0.01	---	0.03	---
P_2O_5	0.31	0.20	0.25	0.14
S	negl.		negl.	
Total	99.37	99.80	99.86	99.58
R_2O_3	21.78		21.07	
Tot. Fe as Fe_2O_3	4.72		4.28	
Na_2O+K_2O/CaO	1.55		1.73	
Fe_2O_3/FeO	0.84		1.06	
Tot. Fe as Fe_2O_3 + MgO+MnO	6.70		6.08	

Column

1 D. Maynes, analyst.

2 Calculated from mode A-112-1

3 D. Maynes, analyst.

4 Calculated from mode A-69.

TABLE 18. MODAL COMPOSITION OF A-112-N AND A-60-P

	Weight %	
	A-112-N	A-69-P
Quartz	18.85	20.35
Orthoclase	14.75	16.95
Albite	28.4[a]	28.1[b]
Anorthite	15.5[a]	15.1[b]
Biotite	7.2	7.55
Hornblende	8.7	4.95
Magnetite	2.1	2.65
Sphene	0.7	1.45
Apatite	0.4	0.3
Zircon	0.1	0.25
Chlorite	0.55	1.0
Plag. alt. min.	2.75[c]	1.3[c]
Total	100.00	99.95
Plag. comp.	An 35[a]	An 35[b]

a. Calculated from 45.65 volume % plagioclase assuming 85% An 38 and 15% An 20.

b. Calculated from 44.75 volume % plagioclase assuming 85% An 37 and 15% An 23.

c. Using the specific gravity of muscovite (2.7).

The chemical analysis of A-69-P contains 15 percent less FeO, 10 percent less CaO, and 9 percent less MgO than the analysis of A-112-N. There is 1.8 percent more SiO_2 in the analysis of A-69-P than in the analysis of A-112-N. The remaining oxides are the same in the two analyses within the experimental error. These comparisons do not show directly the true differences in chemical composition between the porphyritic granodiorite and the nonporphyritic granodiorite, because the modal composition of the two analyzed rocks are not the same as the average modal composition of their respective rock types. However, if the differences in chemical composition between the specific analyzed rocks and their respective average rock types are estimated from the modal data, then meaningful comparisons can be made between the average rock types. For example, the average nonporphyritic granodiorite contains less plagioclase than the average porphyritic granodiorite (Table 16), but the analyzed nonporphyritic granodiorite A-112-N contains more plagioclase than the analyzed porphyritic granodiorite, A-69-P (Table 18). Similar reversals in relative abundance exist for biotite, magnetite and orthoclase. If these corrections could be made, it would probably become apparent that the average porphyritic granodiorite contains at least two weight percent more SiO_2 and significantly more Na_2O than the average nonporphyritic granodiorite. FeO, Fe_2O_3, P_2O_5, and probably MgO, TiO_2 and K_2O are more abundant in the average, relatively unaltered nonporphyritic granodiorite. The two textural types of Alta granodiorite probably contain the same amount of CaO, Al_2O_3, and MnO. However, it is impossible accurately to normalize the chemical data without additional modal data for the two rock types.

In order to check the validity of the modal analyses as an estimate of the chemical composition of the rock, a chemical composition was calculated from the modal and mineralogical data for both rocks. Optical data were used to determine the average composition of the plagioclase. Stoichiometric formulae were used for the composition of quartz, sodium-free orthoclase, magnetite, iron-free sphene, zircon and apatite. The chemical analyses of the hornblende and biotite from A-112-N were used for the composition of these minerals in both A-112-N and A-69-P. The stoichiometric formula of muscovite was used as an estimate of the composition of the plagioclase alteration minerals, and the stoichiometric formula of penninite was used to approximate the composition of the chlorite. The resulting chemical compositions are shown in columns 2 and 4 of Table 17. The agreement between the wet chemical and calculated chemical compositions is good. In both calculated analyses there is slightly more CaO, MgO, FeO and K_2O and less Na_2O, SiO_2 and Al_2O_3 than in the corresponding chemical analyses. The tendency to overestimate dark-colored minerals in the mode (Chayes, 1956, p. 99) accounts for the higher CaO, MgO and FeO in the calculated compositions of both A-112-N and A-69-P. Higher K_2O and sympathetically lower Na_2O in the calculated compositions are probably due to the assumption that the composition of the orthoclase is pure $KAlSi_3O_8$ and that the plagioclase alteration mineral is muscovite. Attributing all the excess Na_2O in the calculated analyses to albite in solid solution in the orthoclase gives an approximate composition of the alkali feldspar of Or85-Ab15 in the case of A-112-N and Or80-Ab20 in the case of A-69-P. The higher TiO_2 con-

tent in the calculated analysis for A-69-P indicates that some of the fine-grained mineral in chlorite which was recorded as sphene in the modal analyses may be some other mineral instead.

Mineral compositions were calculated for the chemical analyses of A-69-P and A-112-N and for two of the three older analyses listed in Table 3. These data are found in Table 19. To obtain the calculated mineral composition, the chemical analyses were cast in terms of cation numbers and then the observed minerals were calculated in the following order: apatite, sphene, provisional orthoclase, provisional albite, anorthite and magnetite. The excess Ca was combined with enough provisional albite and Fe + Mn + Mg to form hornblende, $NaCa_2(Fe, Mn, Mg)_5AlSi_7O_{22}(OH)_2$. The remaining Fe + Mn + Mg was combined with provisional orthoclase to form biotite, $K(Fe, Mn, Mg)_3(AlSi_3O_{10})(OH)_2$. Orthoclase and albite were then calculated by subtracting the amounts allotted to hornblende and biotite from the provisional minerals. Quartz was determined last by summing the allotted Si and subtracting the total from the Si cation number.

In many respects the relative differences between the calculated mineral compositions of A-69-P and A-112-N are the same as the relative differences between the corresponding modes. Mainly, the porphyritic granodiorite contains more quartz and albite and less anorthite and femic minerals than the nonporphyritic granodiorite. In addition, the composition of the plagioclase is essentially the same in the mode as it is in the calculated mineral composition. In contrast to the modal composition, however, the two rocks contain essentially the same amount of calculated orthoclase.

TABLE 19. CALCULATED MINERAL COMPOSITION OF A-69-P AND A-112-N

			Older Analyses*	
	1	2	3	4
	A-112-N	A-69-P		
Quartz	19.91	21.99	15.15	20.73
Orthoclase	13.44	13.50	16.31	15.37
Albite	34.11	34.92	34.96	35.38
Anorthite	17.81	16.86	18.68	16.09
Hornblende	0.94	---	3.00	1.54
Biotite	9.68	8.85	8.03	6.71
Magnetite	2.15	2.21	2.39	2.46
Sphene	1.29	1.11	1.11	1.17
Apatite	0.67	0.53	0.36	0.53
Total	99.98	99.97	99.99	99.98
Plag. comp.	An 34	An 33	An 35	An 30

*Calkins and Butler (1943, p. 34). See Table 3 for the analyses. The sample locality of 3 is "the dump of Steamboat tunnel, Snake Creek." The sample for analysis 4 is listed simply as "granodiorite of the Alta stock."

Column 3 of Table 19 is the mineral composition calculated from an analysis given by Calkins and Butler (1943, p. 34, col. 4) of a sample collected from the dump of Steamboat Tunnel south of the Alta stock. No geologic map of the mine is available, but the workings probably do not extend very far into the stock. Relative to the A-112-N, this rock contains less quartz and more anorthite, albite and hornblende and may represent the border rock. During this study, sample A-14-N was collected from this same dump. Although the mode of this rock is included with the other nonporphyritic granodiorites in Table 11, it contains more hornblende and less quartz than any of the other nonporphyritic granodiorites listed in the table. A-14-N does not, however, have the extreme modal composition of the border rock.

Column 4 of Table 19 is calculated from an analysis given by Calkins and Butler (1943, p. 34, col. 2) but the sample location is not known other than the general area of the stock between Brighton and Alta.

Summary. Geologic relations and compositional comparisons, supported by petrographic evidence to be discussed later, the major rock types can be arranged in the following sequence from the presumably oldest, least silicic rock type to the youngest most silicic rock type: (1) border rock, (2) nonporphyritic granodiorite, (3) subporphyritic granodiorite, (4) porphyritic granodiorite. This sequence indicates the direction in which the abundance of the mafic minerals decreases and the abundance of quartz increases. The prealteration biotite-hornblende ratio increases regularly toward the more silicic end of the series.

The modal data indicate a strong change in composition going from the border rock to the nonporphyritic granodiorite. The chemical analyses as well as the modal data indicate a slight change toward a

more silicic composition between the time of crystallization of the nonporphyritic granodiorite and the later solidification of the porphyritic granodiorite. Comparison of the two chemical analyses shows that the porphyritic granodiorite contains more SiO_2, a higher ratio of alkalis to lime, higher Fe_2O_3/FeO and less femic oxides than the nonporphyritic granodiorite. Both the calculated mineral compositions and the modal data show the porphyritic granodiorite contains more quartz and less biotite, hornblende, apatite and sphene and possibly magnetite than the nonporphyritic granodiorite. The calculated mineral compositions indicate that the orthoclase and plagioclase content is the same in the two major textural types of granodiorite. On the other hand, the modal data indicate the porphyritic granodiorite contains less orthoclase and more plagioclase than the nonporphyritic granodiorite. The modal composition of the phenocryst assemblage of the porphyritic rock has felsic mineral ratios similar to those of the border rock. The groundmass of the porphyritic rock has a granitic composition and can be considered the silicic extreme of the compositional sequence.

Texture

A detailed textural study may provide information from which the crystallization history of the major rock types can be inferred. Because the differences in crystallization history between the major intrusive rock types may have significance to the ore-forming process, it is desirable to express the differences and similarities in texture in quantitative terms.

The principal difference between the two major textural types of

granodiorite is one of grain-size distribution. Three terms used to describe grain-size distribution are equigranular, seriate and porphyritic. Figure 9 is a schematic histogram plot of grain size vs. abundance and shows the grain-size distribution implied in each of these textural terms. Figure 9A shows the unimodal distribution in a hypothetical equigranular rock. Seriate (Fig. 9B) is "a textural term applied to granular rocks in which the sizes of the crystals vary gradually or in a continuous series" (Howell, 1957, p. 262). The nonporphyritic rocks have a continuous series of grain sizes from 0.05 to 10.0 mm, and although most of the rock is made up of grains between 0.5 and 5.0 mm, the grain-size distribution can be described as seriate. The grain-size distribution of the porphyritic granodiorites is shown in Figure 9C. Although the rock has a bimodal grain-size distribution, the phenocryst assemblage of the porphyritic rocks has approximately the same seriate grain-size distribution with the same mean size as the nonporphyritic granodiorites. The groundmass of the porphyritic rocks can be described as equigranular.

A schematic plot of grain-size distribution of subporphyritic granodiorites would differ from that of the porphyritic granodiorites (Fig. 9C), only in the location and height of the peak which represents the groundmass.

Two other terms used in describing the grain-size distribution of the rocks of the Alta stock are nonporphyritic and inequigranular. Nonporphyritic means not having a bimodal distribution and therefore implies either a seriate or an equigranular grain-size distribution. All the

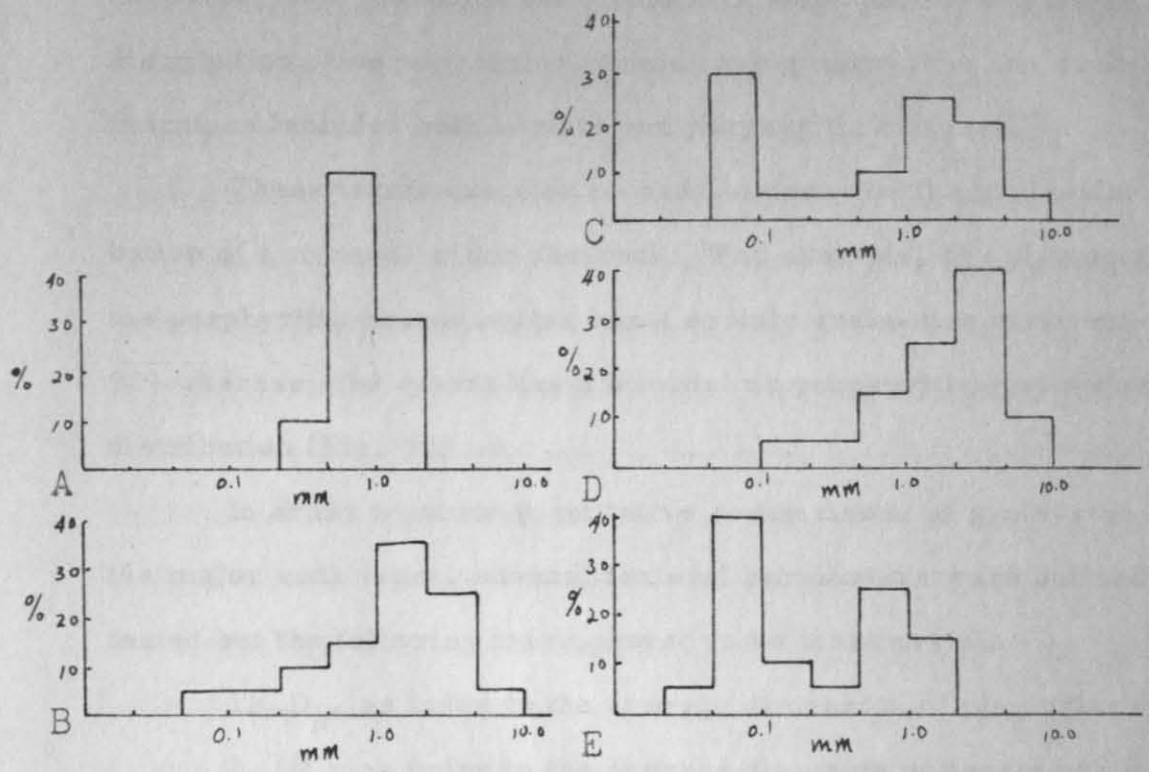


Figure 9. Grain-size distribution. Schematic plot of grain size vs. abundance (in volume %).

A. Equigranular grain-size distribution.

B. Seriate grain-size distribution in the nonporphyritic granodiorites.

C. Bimodal grain-size distribution in porphyritic granodiorites.

D. Seriate grain-size distribution of plagioclase in porphyritic rocks.

E. Bimodal grain-size distribution of quartz in porphyritic granodiorite.

nonporphyritic granodiorites in the Alta stock have a seriate grain-size distribution. Inequigranular means having more than one grain size and therefore includes both seriate and porphyritic textures.

These terms can also be used to describe the grain-size distribution of a mineral within the rock. For example, the plagioclase in the porphyritic granodiorites has a seriate grain-size distribution (Fig. 9D) whereas, the quartz has a bimodal or porphyritic grain-size distribution (Fig. 9E).

In order to make quantitative comparisons of grain-size between the major rock types, several textural parameters were defined and tested but the following three proved to be most useful.

1. D_p, an index to the average dimension of plagioclase crystals.
2. D_q, an index to the average diameter of quartz grains.
3. I.C., the index of coarseness, or the average distance between grain boundaries.

The first parameter is determined by selecting the 10 largest plagioclase grains seen in a thin section. D_p is equal to the average length of these ten grains measured parallel to the trace of the 010 cleavage. The procedure is to measure 15 to 25 of the apparent largest grains in thin section, and then to select the ten largest of these values.

The second parameter, D_q, is determined by selecting the 10 largest quartz grains in a thin section in the same manner described for D_p. However, the measurements for D_q are the maximum internal diameters of the ten largest grains. D_q is the average of these ten measurements. Both D_p and D_q are dependent on mineral abundance,

grain-size distribution, grain geometry and grain orientation in the thin section. If mineral abundance, grain geometry and grain orientation are the same for all the rocks to be compared, then the parameters should be sensitive to differences in grain-size distribution. The way in which D_p and D_q are measured is shown on photomicrographs of porphyritic and nonporphyritic granodiorite in Figure 10.

The index of coarseness, I.C., is measured with 100x magnification and a mechanical stage. A traverse is made across the part of the slide of interest and the number of grain boundaries crossed by the vertical cross hair is recorded. The number of grain boundaries encountered in the linear traverse is divided by the length of the traverse to yield the index of coarseness, I.C. In the case of equigranular rocks, this index is often very close to the independent visual estimate of the average grain size of the rock. The I.C. is best suited for use with granular rocks, and would be practically useless in describing graphic granite or other rocks with complicated interpenetration of crystals.

In addition to groundmass grain size, one of the principal differences between porphyritic and subporphyritic granodiorites is the presence of overgrowths on the phenocrysts in the subporphyritic rocks. The technique of point-count modal analysis was used to measure the percentage of the phenocryst assemblage that is present as overgrowths. Both the index of coarseness measurements and the measurements on the relative abundance of overgrowths indicate a complete gradation in texture from porphyritic to subporphyritic granodiorites.

Nonporphyritic granodiorite. Most of the granodiorite in the peripheral part of the Alta stock has a medium-grained, hypidiomorphic

inequigranular texture (Fig. 10A). The major minerals in the nonporphyritic granodiorite have a seriate distribution of grain sizes; more than 75 percent of the rock is made up of grains ranging in size from 0.5 to 3.0 mm. Plagioclase has an average grain size which is slightly larger than that of the other major minerals. Quartz and orthoclase form very irregularly shaped grains interstitial to subhedral plagioclase, hornblende and biotite. In thin sections, these anhedral crystals of quartz and orthoclase have optical continuity over areas as large as three mm in diameter. In addition, orthoclase forms equant anhedral crystals which range from 1 to 7 mm in maximum dimension. Sphene forms subhedral to euhedral crystals 1 to 3 mm long. The average grain-size of hornblende in the border rock is slightly larger than in the less mafic nonporphyritic granodiorite.

The relative age of the minerals as deduced from textural relations is the following: hornblende, biotite, plagioclase and sphene crystallized together and earlier than quartz or orthoclase. Biotite and plagioclase continued to crystallize after hornblende ceased to grow. All or part of the magnetite crystallized later than the hornblende or biotite and probably was contemporaneous with quartz and orthoclase. Orthoclase extensively replaced all other minerals except quartz and forms a few relatively large anhedral grains with abundant inclusions. The textural relations from which this sequence was deduced are the following:

1. Grain contacts between the three major minerals hornblende, biotite, and plagioclase as well as sphene have been the locus for growth of quartz and orthoclase grains.

A.

B.

Figure 10. Photomicrographs showing porphyritic and nonporphyritic texture. The type of measurements taken in determining the textural parameters D_p and D_q are shown by d_p and d_q respectively. Crossed nicols, x10.

A. A-112-N, Albion Basin.
B. A-57-P, 2000 feet west of Mt. Millicent.

2. The prismatic directions of hornblende show control over the shape of plagioclase inclusions. These plagioclase inclusions, in some cases, are in optical continuity with plagioclase crystals outside the hornblende.

3. Very small euhedral "seeds" of biotite, hornblende and apatite are oriented with crystal faces parallel to a plane of compositional zoning in plagioclase, suggesting the contemporaneity of these four minerals.

4. Magnetite octahedra occur on grain boundaries of quartz or orthoclase in contact with plagioclase, biotite, or hornblende. Magnetite also occurs as small subhedral grains inside hornblende and biotite grains. The magnetite is concentrated near the periphery of the biotite grains, but is uniformly distributed throughout the hornblende. The occurrence in mafic minerals probably represents replacement by magnetite, but inclusion of magnetite during growth of the host mineral has not been disproved.

5. In addition to forming separate grains, biotite is common as inclusions in hornblende. Some of these inclusions are tabular crystals with the basal face of the biotite oriented parallel to a prismatic crystal face of the hornblende. This type of biotite inclusion makes relatively straight contacts with the hornblende which are parallel to the crystal directions of the biotite. In some cases the biotite extends beyond the limit of the hornblende crystal. Another kind of biotite inclusion in hornblende has very irregular shapes which are crudely controlled by the crystallography of the hornblende. The first kind of biotite inclusion

suggests simultaneous crystallization of the two minerals. The second kind suggests that biotite replaced the host minerals and therefore is in part later than hornblende.

Porphyritic granodiorite. The porphyritic granodiorite contains the same minerals in approximately the same proportions as the non-porphyritic granodiorite. Moreover, the average grain size of the phenocrysts which make up 65 to 80 percent of the porphyritic granodiorite is the same as the average grain size of the nonporphyritic granodiorite. The textural relations and grain-size distribution of plagioclase, hornblende and biotite are very similar in the two rock types. It is primarily the texture and distribution of the quartz and orthoclase in the porphyritic granodiorite that makes the fabric of these two rock types different (Fig. 10).

Although the phenocrysts are commonly euhedral in outline, considerable departure from well-formed crystal faces is evident. Crystals of plagioclase and orthoclase have good euhedral outlines which are not embayed by the groundmass. In fact, plagioclase in optical continuity with the sodic rims on plagioclase phenocrysts extends into the groundmass. Phenocrysts of quartz have crystal faces but the euhedral outline of the crystal is rounded and deeply embayed by the groundmass. In detail, however, the rounded outline of the quartz grains is not the trace of a smooth surface, and groundmass-size crystals of other minerals are partially or completely enclosed by quartz near the rims of the grains. Biotite phenocrysts have well-developed basal crystal faces, but the prism faces are poorly formed. Biotite does not show deep embayment by the groundmass. Hornblende laths have the typical pseudohexagonal

cross section but the crystal faces are breached and the resulting embayments are filled with plagioclase, orthoclase and quartz. Moreover, the hornblende contains anhedral biotite, which in some cases is related to the embayments.

Although the groundmass is composed predominantly of quartz and orthoclase, small grains of apatite, magnetite, biotite and hornblende also are found in the porphyritic rocks. These minerals, however, do not have a bimodal distribution of grain size as do quartz and orthoclase, and the grain-size distribution of these minerals is the same in both nonporphyritic and porphyritic granodiorites. Magnetite forms grains which, in general, are slightly larger than the average grain size of the groundmass. Apatite is found as 0.05-mm crystals in both coarse- and fine-grained groundmass. In general, it is not possible to conclude that the apatite, magnetite and finer grained biotite and hornblende are genetically related to the quartz, orthoclase and plagioclase of the groundmass. On the other hand, the fine-grained hornblende and biotite in the porphyritic rocks of the selvaged contacts with nonporphyritic granodiorite is evidence that suggests that these minerals did crystallize in part with the groundmass assemblage.

Hornblende, biotite, and plagioclase have a seriate grain-size distribution in both porphyritic and nonporphyritic granodiorite. The average crystal size of each of these three minerals is approximately the same in all thin sections of the two rock types. To test this apparent similarity, the textural parameter D_p, the average apparent length of the ten largest plagioclase grains, was measured in six thin sections of

porphyritic granodiorite and seven thin sections of nonporphyritic granodiorite. The measurements and the averages for each textural type are presented in Table 20. There is essentially no significant difference in size of the plagioclase grains in the two rock types.

Even in a cursory examination of thin sections, one is impressed with the difference in size and character of quartz and orthoclase in the two types of granodiorite. In the nonporphyritic granodiorite these two minerals form very irregularly shaped grains interstitial to the other major minerals. In the porphyritic granodiorite, quartz forms equant, rounded, bipyramidal crystals having simple, regular contacts with the groundmass; and orthoclase forms equant grains with rectangular outline. The average size of the quartz and orthoclase phenocrysts in the porphyritic granodiorite appears to be larger than the average size of the corresponding grains in the nonporphyritic granodiorite. To test this observation, the textural parameter D_q, the average maximum internal diameter of the ten largest quartz grains seen in a thin section, was measured in both porphyritic and nonporphyritic granodiorite. The results are found in Table 20 and show that the quartz phenocrysts in the porphyritic granodiorite are 30 percent larger on the average than quartz grains of the nonporphyritic granodiorite.

Index of coarseness measurements (I.C.) were made in thin sections of porphyritic rocks to obtain a quantitative estimate of the grain size of the groundmass. The data are found in Table 21 and show that the I.C. values of the groundmass of porphyritic rocks range from 0.024 to 0.150 mm. The range of grain size in the groundmass within a

TABLE 20. VALUES FOR TEXTURAL PARAMETERS Dp AND Dq FOR THIN SECTIONS OF ALTA GRANODIORITE

Nonporphyritic granodiorite

Sample	Dp (mm)	Dq (mm)
A-68-N	3.45	0.7
A-95-1-N	4.2	0.8
A-95-2-N	3.9	0.75
A-112-1-N	2.95	---
A-112-2-N	3.7	0.7
A-137-N	3.6	0.55
A-230-N	3.9	1.15
Average	3.65 ± 0.25	0.8 ± 0.15

Porphyritic granodiorite

Sample	Dp (mm)	Dq (mm)
A-57-P	3.2	1.05
A-69-1-P	3.4	1.25
A-69-2-P	3.55	1.1
A-78-P	3.95	1.1
A-183-P	3.2	1.0
A-185-P	2.6	0.8
A-186-P	4.3	1.15
A-217-P	4.0	1.0
Average	3.55 ± 0.5	1.05 ± 0.1

Subporphyritic granodiorite

Sample	Dp (mm)	Dq (mm)
A-3-1-S	3.2	1.15
A-3-2-S	3.9	1.1
A-3-3-S	3.45	--
A-58-1-S	3.8	1.1
A-58-2-S	4.25	--
A-60-S	3.45	0.85
A-182b-S	3.4	1.25
Average	3.65 ± 0.35	1.1 ± 0.1

TABLE 21. INDEX OF COARSENESS MEASUREMENTS

Sample (prefix A-)	I. C.* mm	Sample	I. C. mm
3-S	0.13	212-P	0.107
58-S	0.21	217-P	0.069
60-S	0.145	220-P	0.14
69-1-P	0.052	226-P	0.080
69-2-P	0.056	307-P	0.060
61-S	0.140	313-N	0.25
63-P	0.055	317-S	0.088
67-P	0.095	319-P	0.135
78-P	0.024	322a-P	0.104
82-P	0.160	322b-S	0.15
151-P	0.045	95-N	0.425
167-P	0.095	108-AP	0.12
182b-S	0.153	209-N	0.37
182c-P	0.060	214-AP	0.12
183-P	0.038	215-L	0.295
185-P	0.138	219-1-L	0.26
186-P	0.15	219-2-L	0.28
187-S	0.21		

* The index of coarseness measurements were made on the groundmass of the porphyritic granodiorite (-P), subporphyritic granodiorite (-S) and the leucocratic quartz monzonite dikes (-L). Similar measurements were made on the grain boundaries in the interstitial quartz and orthoclase in the nonporphyritic granodiorites (-N). All major mineral grains were included in the measurements on the aplite-pegmatite dikes (-AP).

thin section of any one sample is small compared to the range of I.C. measurements between samples.

The relative age of the minerals in the porphyritic granodiorite as deduced from textural evidence, is the following: hornblende, plagioclase, biotite and sphene are early, with hornblende probably the earliest mineral; quartz, orthoclase, minor plagioclase and magnetite are later. Hornblende phenocrysts are deeply embayed and are replaced in part by anhedral plagioclase and biotite, indicating that hornblende had completed crystallization and was being actively resorbed by the magma when the groundmass started to crystallize. Relative to orthoclase, the abundance of quartz in the phenocryst assemblage is relatively high. The quartz phenocrysts are embayed but also have quartz overgrowths. These relations suggest two periods of quartz growth and that quartz began crystallizing before orthoclase. Although there is no evidence that biotite crystallized with the groundmass, the lack of embayment of the biotite phenocrysts indicates this mineral was stable when the groundmass began to crystallize. Both the sodic rims on the plagioclase phenocrysts and the fine-grained plagioclase crystallized with the groundmass, but 80 percent of the plagioclase had crystallized before the groundmass was formed.

Subporphyritic granodiorite. The textural characteristics most common in the subporphyritic granodiorite are the following: (1) a poorly-defined bimodal distribution of grain size for quartz and orthoclase, (2) overgrowths on quartz and orthoclase phenocrysts (Fig. 11), (3) an index of coarseness of the groundmass between 0.14 and 0.21 mm, and (4) a subgraphic intergrowth of quartz and orthoclase interstitial to the plagioclase,

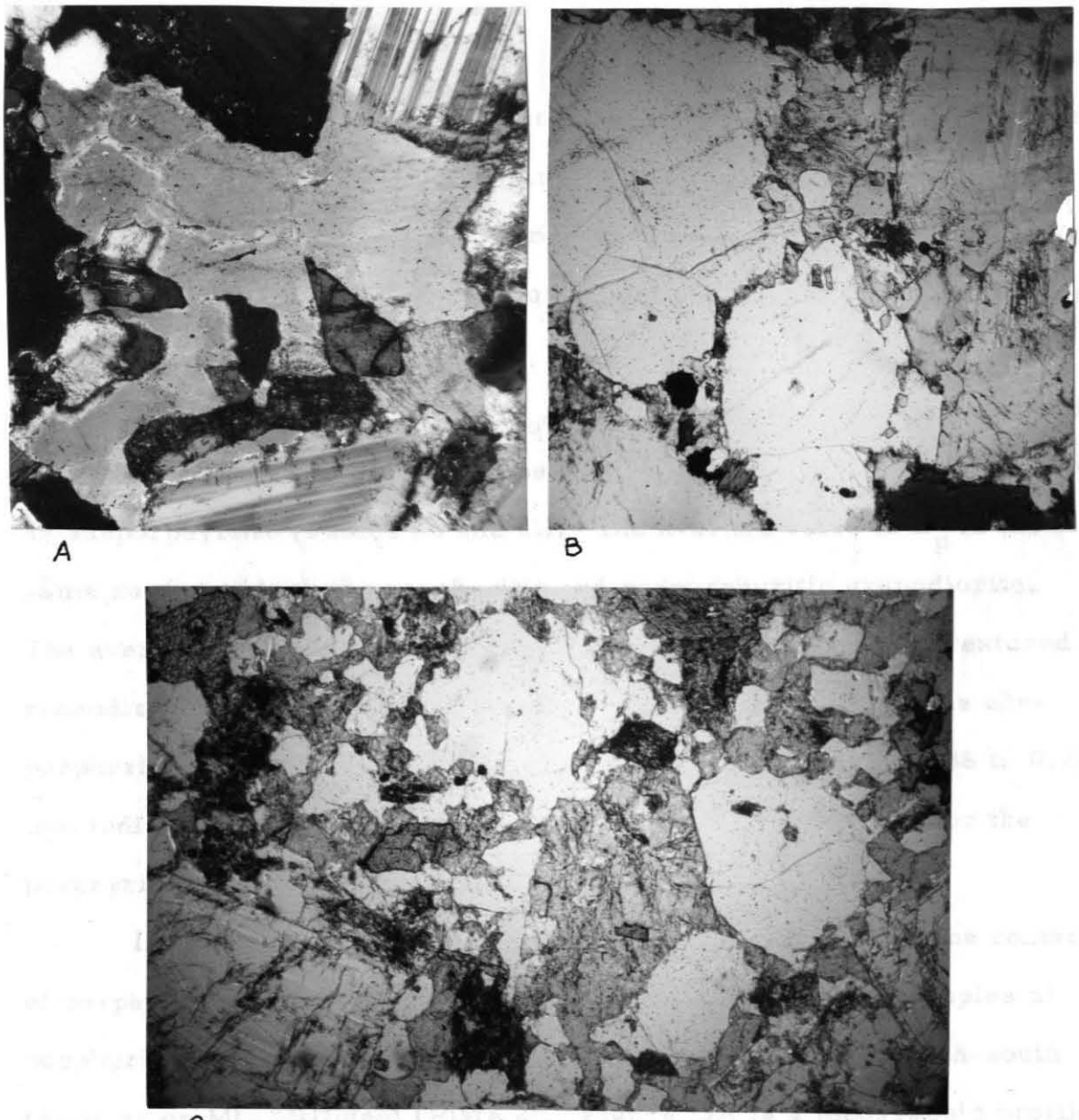


Figure 11. Texture of quartz.

A. Interstitial quartz in A-112-N. Crossed nicols, x25.

B. Quartz phenocrysts with overgrowths in subporphyritic granodiorite A-61-S. Very little interstitial groundmass. Plane light, x25.

C. Quartz phenocrysts in subporphyritic granodiorite A-185-S with high percentage of relatively coarse-grained groundmass. Plane light, x25.

biotite and hornblende in the rock. There is a gradation in each of these features between strongly porphyritic and nonporphyritic textured rocks. The gradation in texture from strongly porphyritic to subporphyritic is shown in Figure 12. The textural relations of hornblende, biotite, plagioclase and sphene in the subporphyritic rocks are the same as they are in the porphyritic rocks.

The textural parameters D_q, D_p, and I.C. were measured in thin sections in which the texture had been previously described qualitatively as subporphyritic (Tables 20 and 21). The average value of D_p is the same as that of both the porphyritic and nonporphyritic granodiorite. The average value of D_q is the same as that of the porphyritic textured granodiorite, and significantly larger than the average D_q of the nonporphyritic granodiorite. I.C. measurements range from 0.088 to 0.21 mm indicating considerable overlap with I.C. measurements for the porphyritic granodiorite.

In order to study the textural changes associated with the contacts of porphyritic granodiorite, thin sections were cut from 11 samples of porphyritic and subporphyritic granodiorite collected on a north-south traverse on Mt. Millicent (Plate 2). Figure 13A is a topographic profile of the traverse showing location and elevation of the samples, and position of the contacts of the porphyritic granodiorite. The contacts were drawn in from data projected from points off the line of traverse. The contact on the south is projected from the well-developed selvage zone which separates the rock types at A-326-P. The contact on the north was drawn on the presence or absence of well-developed quartz phenocrysts

Figure 12. Gradation in texture from porphyritic (A) to sub-porphyritic (E). Photomicrographs of thin sections from five samples collected on Mt. Millicent traverse (Plate 2). Crossed nichols, x40.

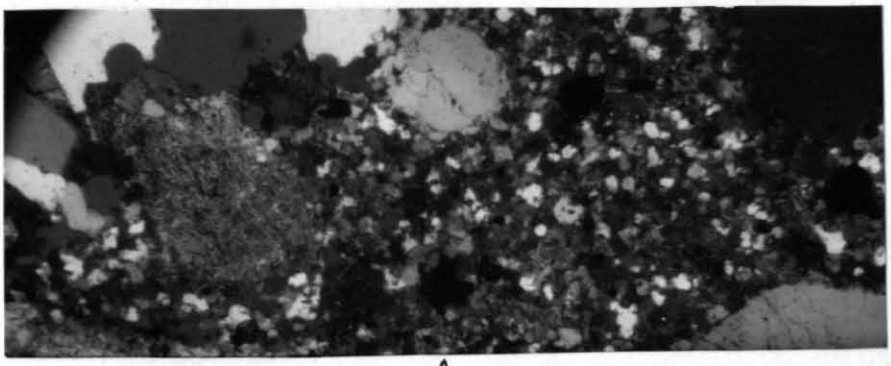
A. A-183-P, I.C. 0.038

B. A-217-P, I.C. 0.069

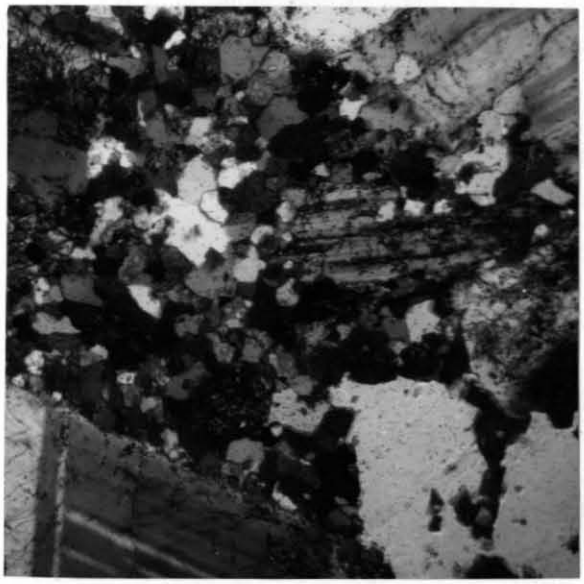
C. A-185-P, I.C. 0.138

D. A-182b-S, I.C. 0.153

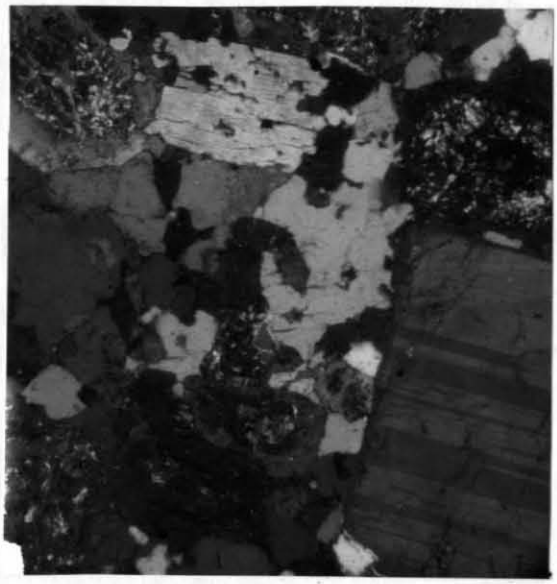
E. A-187-S, I.C. 0.210



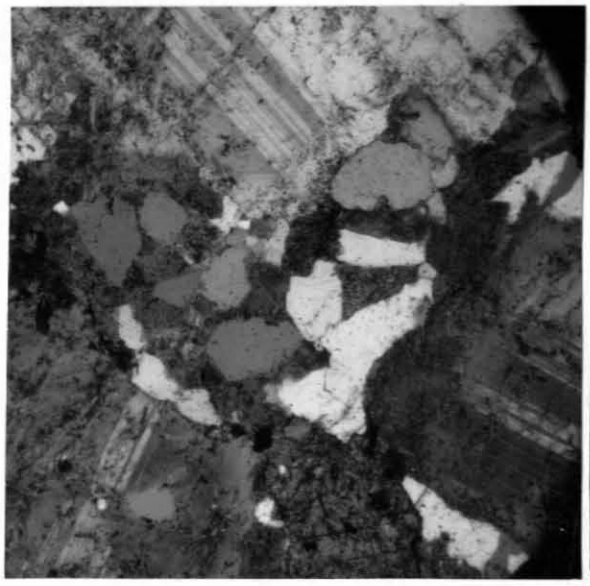
A.



B.



C.



D.

E.

Figure 12. Gradation in texture from porphyritic to subporphyritic.

Figure 13. Variation of textural parameters on a north-south traverse across the porphyritic granodiorite. See Plate 2 for location of traverse.

A. Cross section showing sample location.

B. Quartz-orthoclase ratio in the phenocryst assemblage.

C. Quartz overgrowths x 100/quartz phenocrysts + quartz overgrowths.

D. Index of coarseness of the groundmass.

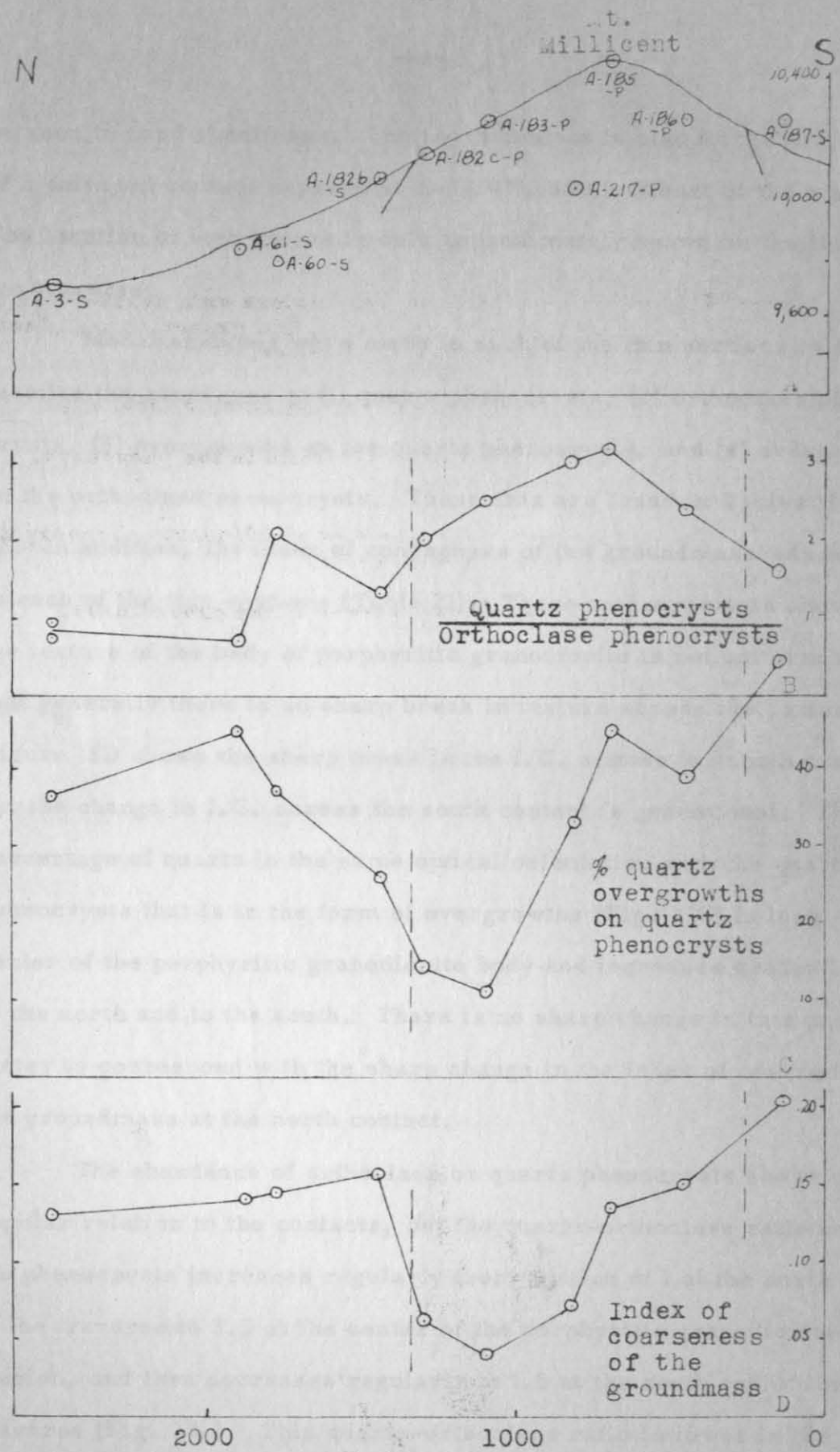

Mt. Millicent
N
S
10,400
10,000
9,600
A-185-P
A-183-P
A-186O-P
A-187-S
A-182c-P
A-182b-S
A-217-P
A-61-S
A-60-S
A-3-S
Quartz phenocrysts / Orthoclase phenocrysts
B
% quartz overgrowths on quartz phenocrysts
C
Index of coarseness of the groundmass
D
2000
1000
0
Feet

Figure 13.

as seen in hand specimens. The north contact is also on the projection of a selvaged contact exposed at A-235-N, 400 feet east of the traverse. The location of both traces is only approximately known on the line of the traverse.

Modal analyses were made in each of the thin sections to determine the abundance of (1) quartz phenocrysts, (2) orthoclase phenocrysts, (3) overgrowths on the quartz phenocrysts, and (4) overgrowths on the orthoclase phenocrysts. These data are found in Tables 13 and 22. In addition, the index of coarseness of the groundmass was measured in each of the thin sections (Table 21). These measurements show that the texture of the body of porphyritic granodiorite is not uniform and that generally there is no sharp break in texture across the contacts. Figure 13D shows the sharp break in the I.C. across the north contact, but the change in I.C. across the south contact is gradational. The percentage of quartz in the same optical orientation with the quartz phenocrysts that is in the form of overgrowths (Fig. 13C) is least in the center of the porphyritic granodiorite body and increases gradually both to the north and to the south. There is no sharp change in this parameter to correspond with the sharp change in the index of coarseness of the groundmass at the north contact.

The abundance of orthoclase or quartz phenocrysts shows no regular relation to the contacts, but the quartz-orthoclase ratio among the phenocrysts increases regularly from a value of 1 at the north end of the traverse to 3.3 at the center of the porphyritic granodiorite intrusion, and then decreases regularly to 1.5 at the south end of the traverse (Fig. 13b). This quartz-orthoclase ratio is lower in the sub-

TABLE 22. PARTIAL MODAL ANALYSES OF PORPHYRITIC AND SUBPORPHYRITIC GRANODIORITE

volume %

	A-60-S	A-61-S	A-182b-S	A-182c-P	A-183-P
Quartz					
phenocrysts	4.5	10.9	11.9	7.3	9.2
overgrowths	2.65	1.5	4.5	1.3	1.2
Orthoclase					
phenocrysts	2.1	7.4	9.0	3.7	3.7
overgrowths	0.9	5.8	2.3	1.5	0.4

	A-58-S	A-185-P	A-186-P	A-187-S	A-217-P
Quartz					
phenocrysts	7.6	3.8	6.5	4.0	5.2
overgrowths	--	3.2	4.2	4.7	2.6
Orthoclase					
phenocrysts	1.75	1.2	2.7	2.4	1.7
overgrowths	--	0.6	1.6	1.7	0.9

porphyritic rocks at the ends of the traverse than in the porphyritic rocks in the middle primarily because more orthoclase was reported as phenocrysts in the subporphyritic rocks. This in turn is probably the result of two factors: (1) some orthoclase in the subporphyritic rocks probably occurs as porphyroblasts formed by replacement of the surrounding minerals, and (2) the difficulty of distinguishing orthoclase which has grown in this manner from orthoclase grains which were formerly intratelluric crystals in a magma. Quartz phenocrysts in the subporphyritic rocks do not form porphyroblasts, but have grown by enveloping, but not replacing, groundmass grains. In summary, the quartz-orthoclase ratio is probably not a simple function of original abundance and distribution of quartz and orthoclase phenocrysts in the magma, but most likely also reflects the greater porphyroblastic development of orthoclase in the subporphyritic granodiorite.

From textural relations on the Mt. Millicent traverse, the following conclusions can be made:

1. The porphyritic granodiorite does not have a uniform, strongly porphyritic texture within the contacts of the intrusion.
2. There is a complete gradation in texture between subporphyritic and porphyritic rocks.
3. The phenocrysts of quartz and orthoclase continued to grow after the groundmass was nucleated.
4. The abundance of quartz overgrowths is less in the porphyritic rocks with the finer grained groundmass.
5. However, the parameters I.C. and relative abundance of

overgrowths on quartz phenocrysts vary somewhat independently. For instance, the value of I.C. has a sharp break across the north contact of the intrusion of porphyritic granodiorite but the change in the relative abundance of quartz overgrowths is gradational.

Other variations on the porphyritic texture undoubtedly exist in the intrusion of porphyritic granodiorite. Thin sections cut from samples collected from the glaciated outcrops north of Lake Mary show porphyritic granodiorite with a very low percentage of groundmass. Some rocks from this area look very similar in this section to nonporphyritic granodiorite, but differ from it in that generally they contain much better developed quartz in the equant, 1-mm grains more typical of the porphyritic granodiorite (Fig. 14). In other thin sections in this area the rock lacks the well-developed quartz and the texture is indistinguishable from that of the nonporphyritic granodiorite. These samples may represent cognate inclusions of nonporphyritic granodiorite. The extent of this textural variety of granodiorite or its relation to the strongly porphyritic granodiorite is unknown.

Course of crystallization. The order in which the minerals crystallized is the same in all textural varieties of granodiorite. Hornblende is the earliest mafic mineral; biotite is in part contemporaneous with the hornblende but most of it is younger. Plagioclase crystallized during most of the history of the magma; it began crystallization as An 50 and ended crystallization with a composition of An 25. Orthoclase is contemporaneous with quartz and both generally are later than hornblende,

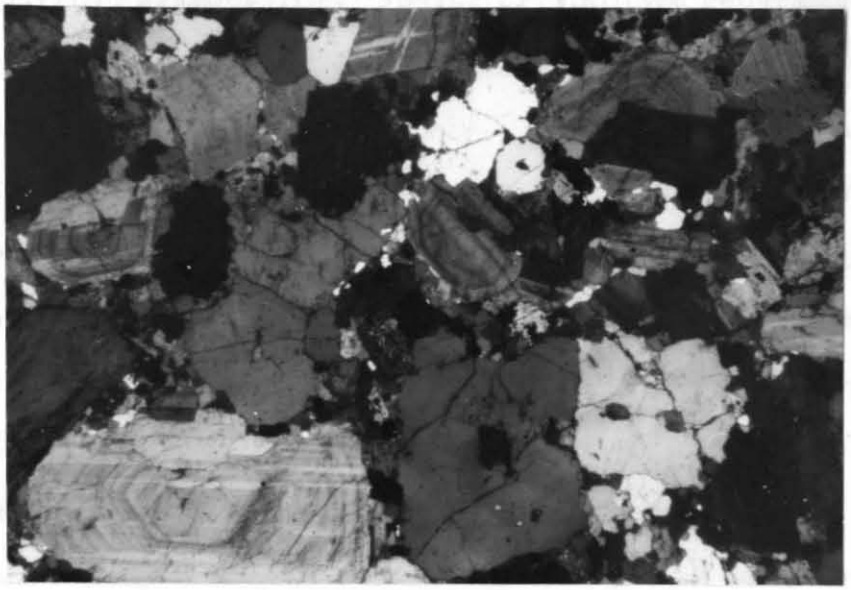


Figure 14. Photomicrograph of A-319-S, 1000 feet north of Lake Mary. This rock is included in the porphyritic granodiorite because of its sample location and the well-developed quartz grains (Q). The rock contains approximately 10 percent fine-grained groundmass. Crossed nicols, x10.

biotite and plagioclase. Quartz began crystallizing before orthoclase in the porphyritic granodiorite. Sphene crystallized generally later with plagioclase, orthoclase and quartz.

On the basis of texture, the crystallization history of all types of granodiorite can be divided into two stages: (1) an earlier stage in which growing crystals could move freely in the magma, and (2) a later stage characterized by a lower percentage of liquid and little relative movement of adjacent crystals. In the first stage euhedral crystals of plagioclase, hornblende, biotite, and sphene grew as intratelluric crystals in the magma of the nonporphyritic granodiorite, and these four minerals along with quartz and orthoclase grew as euhedral crystals in the magma of the porphyritic granodiorite.

In the nonporphyritic granodiorite, the second stage began approximately when the abundance of crystals became greater than the abundance of liquid. Quartz, orthoclase, and magnetite crystals began to grow, and the composition of the crystallizing plagioclase became more sodic. Hornblende and possibly biotite and sphene had stopped crystallizing, and hornblende may have been partly resorbed by the magma. The euhedral form of the earlier crystals was altered by the continued growth of quartz, orthoclase and plagioclase crystals in the confined space of the interstitial magma. It is in this later stage that the earlier minerals were in part replaced by orthoclase and quartz. The fact that the size of orthoclase and quartz crystals is comparable to the size of other major mineral grains in the nonporphyritic granodiorite suggests that there was no sharp change in the conditions which control crystal growth, such as

viscosity and rate of heat loss, between the two stages.

In the border rocks, plagioclase, biotite and possibly hornblende continued growing after the second stage of crystallization began. This continued growth of the intratelluric crystals, produced mutually interfering grain boundaries long before quartz and orthoclase began crystallizing.

Textural relations show that the phenocrysts in the strongly porphyritic granodiorite grew while there was still relatively free movement and unconfined growth of crystals in a liquid which formed more than 45 percent of the system. The second stage in the course of crystallization of the porphyritic granodiorite began with the crystallization of the fine-grained groundmass. In the second stage of crystallization in the subporphyritic granodiorite, a large part of the residual liquid from the first stage continued to crystallize as overgrowths on the phenocrysts while the relatively coarse-grained groundmass was crystallizing.

Origin of texture. The texture of an igneous rock is a function of both the composition and cooling history of the magma. The common parameters used to describe texture, such as average grain size and grain-size distribution, are related to rate of nucleation of new crystals and rate of accretion of material to growing crystals. The competition for material between growing crystals and new nuclei is probably a function of the ability of ions to diffuse through the liquid to growing crystal surfaces. Diffusion rates in a magma are dependent on viscosity which is in turn dependent on composition and temperature of the magma. In connection with studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O, Tuttle and Bowen (1958, p. 77) observed

> Compositions near the isobaric ternary minimum are much more viscous than the feldspar and albite-quartz mixtures, but they are not so difficult to crystallize as the Or-Q eutectic mixtures. For example, near the Ab-Or sideline, equilibrium between liquid and crystals can be attained in a few hours, whereas compositions near the isobaric ternary minima require weeks, and mixtures of orthoclase and quartz may require months to attain equilibrium. In a very rough way the viscosity is inversely proportional to the liquidus temperatures except near the Or-Q eutectic. Thus the thermal deep becomes a viscosity maximum.

In addition, many workers have observed that volatiles lower the viscosity of silicate melts.

Application of these observations on the dependence of viscosity and rate of crystal growth on temperature and composition of the silicate melt leads to interesting conclusions on the origin and distribution of textures in the Alta stock.

The earliest major minerals to crystallize, hornblende, biotite and plagioclase, each has approximately the same average grain size in the major intrusive rock types in all parts of the stock. This observation suggests that early in the history of the stock, conditions affecting crystal growth were nearly the same in all parts of the magma chamber. The fact that on the average, crystals of each of these minerals grew to comparable size in all parts of the stock, shows that conditions which affected crystal growth in the border zone not only were the same as those in the rest of the magma chamber, but that these conditions did not change radically during the magmatic history of the rocks at the contact. Initial intrusion of the magma into colder country rock undoubtedly had a pronounced effect on temperature distribution in the magma. The lower temperature at the contact than at the center of the stock, should

have caused rapid growth of smaller-than average crystals at the contact, resulting in a chill zone. The lack of a chill zone and the uniformity of grain size of plagioclase, hornblende and biotite in the stock may indicate rapid mixing by convection of magma from the cooler wall with the hotter magma in the interior of the stock.

Modal and chemical analyses indicate that the nonporphyritic granodiorite and the later porphyritic granodiorite which intrudes it have approximately the same relative proportions of feldspar components and quartz. If conditions affecting crystal growth had remained unchanged, there should be no differences in texture in the stock. In comparing thin sections of the two rock types it is apparent that the later phase of the magma was developing into a rock with a texture different from that of the nonporphyritic granodiorite even before the fine-grained groundmass crystallized. Quartz and orthoclase in the porphyritic rocks form phenocrysts which have larger average grain size and much better crystal development than these minerals have in the earlier nonporphyritic granodiorite. Relative to the crystallization of plagioclase, the minerals quartz and orthoclase began crystallizing earlier in the porphyritic rocks than in the nonporphyritic rocks.

This apparent earlier crystallization of quartz and orthoclase can be caused by any mechanism which increases the ratio of liquid to crystals before the temperature and composition of the magma reach the stability field of quartz and orthoclase. This ratio can be changed in three ways.

1. Crystals of the early-formed minerals act as space-

fillers and would interfere with the growth of later crystallizing minerals. The nonporphyritic granodiorite contains an average of 11.4 percent biotite, hornblende and chlorite, and the porphyritic granodiorite contains 9.4 percent of these minerals. Although the average porphyritic granodiorite contains fewer crystals of mafic minerals to interfere with the crystal growth of orthoclase and quartz, the difference seems hardly large enough to affect the texture of quartz and orthoclase.

2. A higher SiO_2 and $KAlSi_3O_8$ content of the magma would, of course, favor the earlier crystallization of quartz and orthoclase. The mineral compositions calculated from the chemical analyses show that the porphyritic granodiorite contains two weight percent more quartz but no more orthoclase than the earlier crystallizing nonporphyritic granodiorite.

3. A third possibility is that the later phase of the Alta magma crystallized under a higher water-vapor pressure than the magma had during crystallization of the nonporphyritic granodiorite. In the system $KAlSi_3O_8$-$NaAlSi_3O_8$-SiO_2-H_2O, Tuttle and Bowen (1958) found that increased water-vapor pressure above 500 kg/cm^2 moves the position of the boundary curve between the quartz and feldspar fields away from the quartz apex (Fig. 15). A magma of composition A in Figure 15 will start crystallizing quartz sooner at high water-vapor pressure than at low water-vapor pressure. In the system $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O, which is more applicable to the crystallization of a granodiorite, there is probably a similar dependence of the position of the boundary surface of the quartz field on water-vapor pressure.

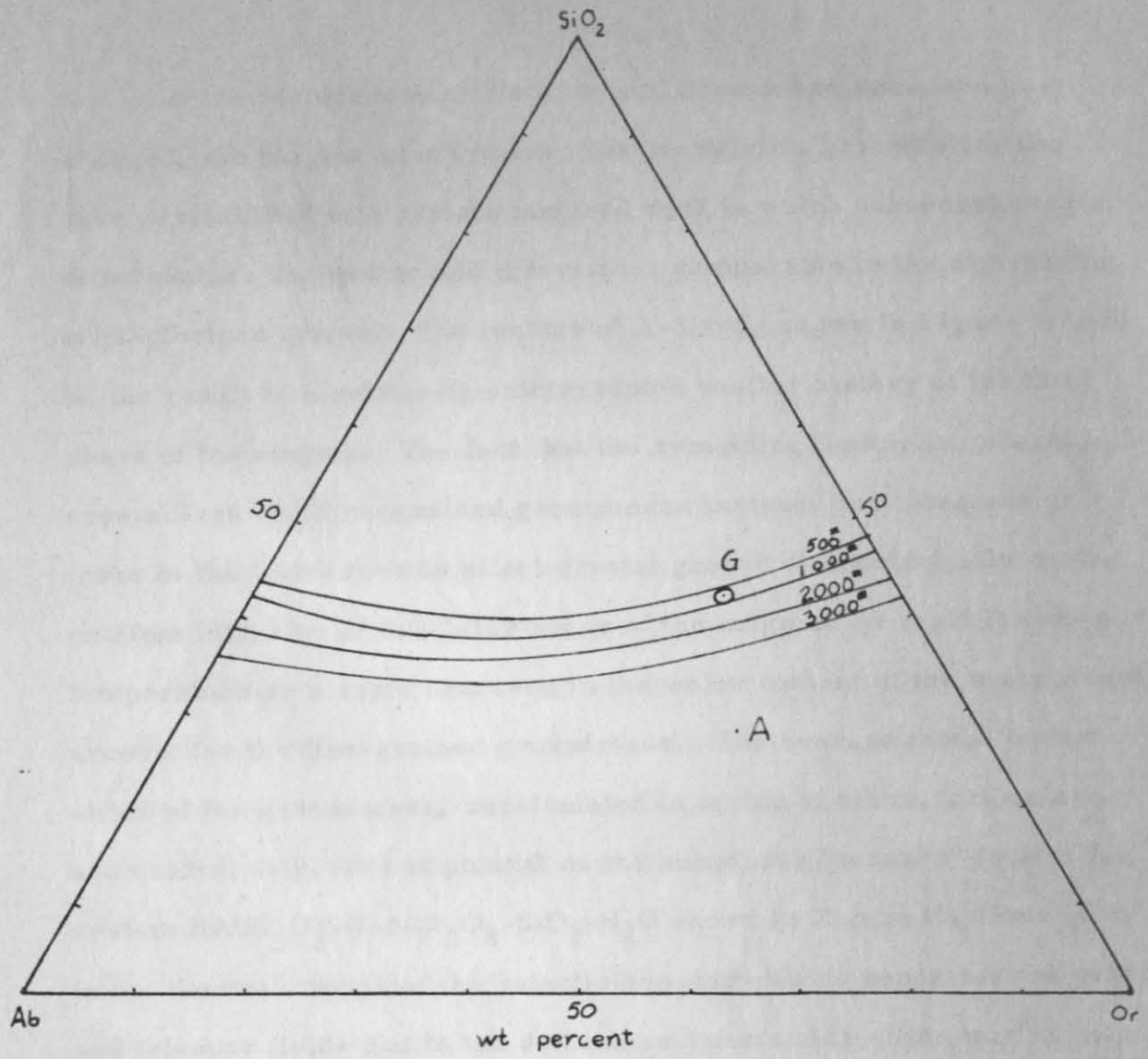


Figure 15. Effect of water-vapor pressure on the quartz-feldspar cotectic boundary in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. After Figure 38 of Tuttle and Bowen (1958). Units of pressure are kg/cm^2.

If the factors which affect crystal growth had remained unchanged, the magma which formed the porphyritic granodiorite should have crystallized to a seriate textured rock in which subhedral crystals of orthoclase and quartz had dimensions comparable to the dimensions of plagioclase grains. The texture of A-319-S, shown in Figure 14 may be the result of a relatively uninterrupted cooling history of the later phase of the magma. The fact that the remaining liquid, in general, crystallized to a fine-grained groundmass instead, indicates one or more of the factors which affect crystal growth changed rapidly during or after intrusion of this later phase of the magma. A rapid lowering of temperature or a rapid decrease in the water content of the magma could account for the fine-grained groundmass. The average modal composition of the groundmass, recalculated in terms of albite, orthoclase and quartz, is plotted at point G on the anhydrous "ternary" face of the system $KAlSi_3O_8$-$NaAlSi_3O_8$-SiO_2-H_2O shown in Figure 15. Point G is in the thermal trough of the cotectic boundary which separates the quartz and feldspar fields and to the orthoclase-quartz side of the minimum. This is the part of the system in which Tuttle and Bowen (1958) report the greatest difficulty in crystallizing synthetic hydrous silicate liquids. A rapid decrease in temperature below the minimum temperature for the system at constant water-vapor pressure would result in a fine-grained groundmass because the high viscosity of the magma would not permit rapid supply of material to the phenocrysts. A decrease in water-vapor pressure by loss of volatiles would further increase the viscosity of the

melt and raise the minimum melting temperature of the system. Both loss of volatiles and a decrease in temperature most likely occurred with intrusion of the later phase of the magma. However, a theory for the origin of the texture of the porphyritic granodiorite must also account for the texture of the subporphyritic granodiorite and the distribution of porphyritic texture within the stock.

The distribution of strongly porphyritic textured rocks does not show a regular relation to the intrusive contacts of the porphyritic granodiorite or to the geometry of the stock. The rocks with the finest grained groundmass are in the center of the stock, and the subporphyritic rocks with coarser grained groundmass are generally located outside the central part of the stock. This distribution of porphyritic texture is not consistent with an origin of the groundmass by rapid lowering of temperature by the intrusion of the later phase of the magma into earlier crystallized, cooler granodiorite.

Release of volatiles through fissures in the overlying cover produced by the emplacement of the porphyritic granodiorite can explain the distribution of porphyritic and subporphyritic textured rocks. The following sequence of events is proposed for the origin of porphyritic and subporphyritic rocks in the Alta stock.

1. The later phase of the magma which crystallized to the subporphyritic and porphyritic granodiorite is a core differentiate of the Alta stock. This core differentiate was nearly saturated with H_2O prior to intrusion into its present position. The water-vapor pressure was only slightly less than the confining pressure. The magma consisted of

approximately 35 percent liquid whose composition was approaching the composition at the minimum melting temperature for the system.

2. Structural adjustments of an unknown cause resulted in emplacement of the later phase of the magma and caused fracturing in the roof material of the stock.

3. In the magma immediately below the fractures, the confining pressure for volatile constituents became considerably less than the water-vapor pressure in the magma. A vapor phase formed and the volatiles, mainly water, began escaping through these fractures. The decrease in water content of the magma caused an increase in the viscosity of the melt and raised the minimum melting temperature of the magma. Volatile constituents began moving from more distant parts of the magma chamber toward the fractures.

4. Freezing of the highly viscous magma at the base of these fractures formed the fine-grained groundmass of the strongly porphyritic granodiorites and tended to seal off the escape routes for water and slowed down the rate of loss of volatiles. The remaining liquid part of the magma contained less water than initially and consequently had a higher viscosity. The interstitial liquid in this magma crystallized as overgrowths on the phenocrysts and as new crystals nucleated in the now viscous liquid. The magma which completed crystallization after the fractures were sealed ended up with a subporphyritic texture. Uneven distribution of volatiles in the remaining pore liquid in the magma could account for variations in texture in the subporphyritic granodiorite.

In the hypothesis suggested above, the subporphyritic granodiorite solidified after the porphyritic granodiorite. The apparent intrusive relations of subporphyritic granodiorite against nonporphyritic granodiorite at the erosional remnant of a selvaged contact between locations A-60-S and A-61-S, 1200 feet north of Mt. Millicent, suggest an alternative hypothesis. Namely, the subporphyritic granodiorite may represent an older intrusive event which did not have as profound an effect on the subsequent crystallization history of the rock as did the intrusion of the porphyritic granodiorite.

MAFIC LAYERED GRANODIORITE

Distribution and Contact Relations

The mafic layered granodiorite is a very dark medium-grained rock, with a pronounced layered internal structure, which forms inclusions in nonporphyritic granodiorite on the west slope of Mt. Wolverine. This rock forms thin tabular bodies which can be traced for as much as 200 feet in outcrop. Although these tabular bodies are large, they are rare; only five with a thickness greater than one foot were found in the stock. These bodies have sharp upper and lower contacts with the enclosing nonporphyritic granodiorite. Laterally, the mafic layered granodiorite grades rather abruptly, through less than a foot of transitional rock, to granodiorite having a normal color index. The sharp contacts and the abrupt terminations of the internal structures indicate that these bodies are inclusions in the nonporphyritic granodiorite. The mafic layered granodiorite bodies are generally darker, thicker, more continuous, less steeply dipping, coarser grained and have sharper contacts than the schlieren of mafic minerals of the border rocks.

Internal Structure

The layered appearance of the mafic layered granodiorite is due to differences in the average crystal size and in the ratio of light to dark minerals in adjacent layers. Approximately 20 conspicuous changes in color index or crystal size can be picked out easily in the 30-inch bed at A-299-ML (Fig. 16). The individual beds having uniform color index and grain size can be traced from inches to several feet along the trace before they lens out between

Figure 16. Mafic layered granodiorite at A-299-ML, 3000 feet west of Mt. Wolverine. Looking south. Note that rock is coarser grained at the base than at the top of the layer just below pen. Typical fine-grained amphibolite inclusion (i) is attached to lower contact with nonporphyritic granodiorite.

layers of different color index or crystal size. A gradational decrease in crystal size without an accompanying change in color index across the layering can be seen in the 7-inch basal layer at A-299-ML and is shown in Figures 16 and 17. This dark layer is thicker than the average and can be traced for 35 feet. Commonly, however, the changes in mineral content or crystal size which produce the layered appearance of the rock are much sharper and occur without any recognizable cycle.

In addition to the compositional and textural layering, the mafic layered granodiorite bodies have another primary planar structure which is the result of the orientation of the longer axes of elongate and tabular crystals parallel to the compositional layering. This planar structure is best shown by hornblende laths and tabular crystals of sphene. Biotite forms both tabular and elongate crystals, but in both cases the long axis of the grain is orientated approximately parallel to the layering. The larger plagioclase tablets also show preferred orientation. In addition to the planarity, there is commonly a pronounced lineation of the hornblende laths. The lineation in the mafic layered rock at A-299-ML is well developed but is not uniform either horizontally or vertically in the outcrop. However, in the slab shown in Figure 17, the lineation is 45° from the direction of the lineation in the enclosing lighter colored granodiorite.

The layering in these rocks has been deformed into three kinds of small-scale structures: (1) folds and faults within the layered bodies, (2) folds which have affected the layered granodiorite but have not affected the enclosing granodiorite, and (3) faults in which the mafic layered granodiorite and the enclosing granodiorite have behaved

Figure 17. Mafic layered granodiorite at A-299-ML.

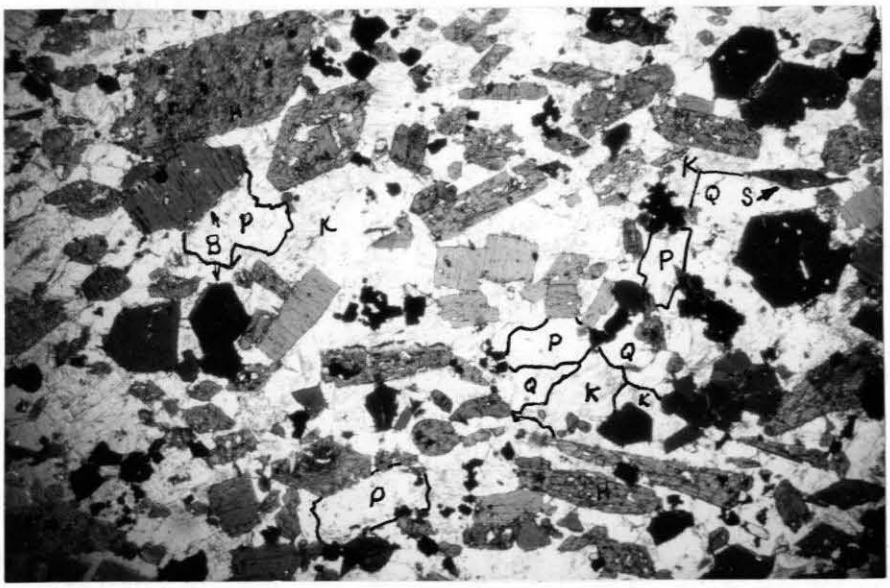
A. Slab opposite block from which thin sections were cut. Visible face of upper slab is oriented perpendicular to the plane of the lower slab.

B. Photomicrograph of A-299-4-ML. Plane light, x10.

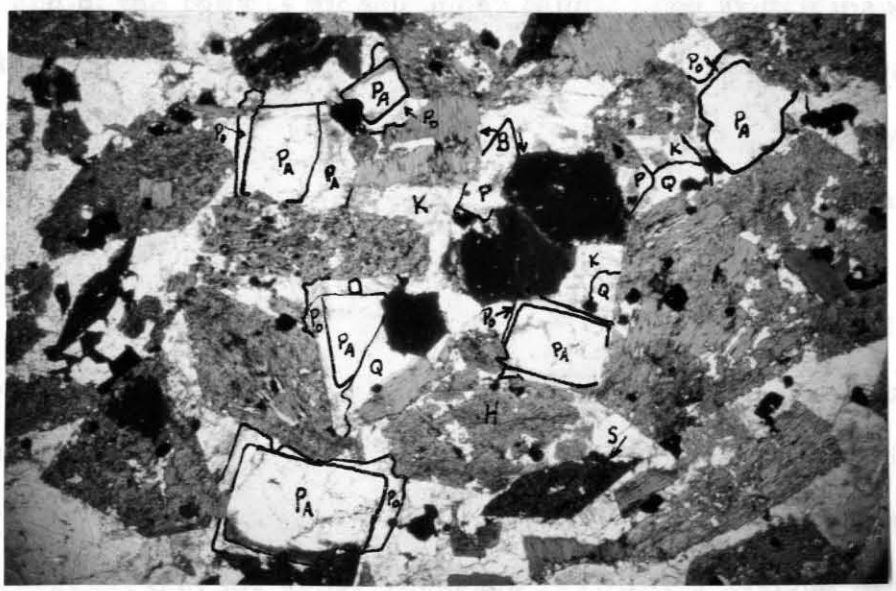
C. Photomicrograph of A-299-3-ML. Plane light, x10.

Note lineation of hornblende crystals in upper slab in A. A fine-grained amphibolite inclusion is found in the non-porphyritic granodiorite on the left end of A. There is a planar orientation of the longer axes of hornblende (H), biotite (B) and sphene (S) perpendicular to the plane of thin sections A-299-3 and -4. Both thin sections have the same modal composition. Euhedral andesine cores (P_A) of plagioclase grains have anhedral oligoclase overgrowths (P_O).

A.



B.



C.

Figure 17. Mafic layered granodiorite at A-299-ML.

as a unit.

Structures of the first type are well developed at A-299-ML and illustrated in Figures 18 and 19. The faulting shown in Figure 18 has affected most of the layers in the body but the basal dark layer is not cut by any of the faults. The gap left at the top of the bed by the dropped block is filled with light-colored granodiorite.

A well exposed example of small-scale folding at A-299-ML which involves only a few layers is shown in Figure 18. The layering above and below this deformed zone is not folded. Other internal structures are more complex, and in some cases the layering has a disaggregated appearance.

An unusual example of crosscutting relations between layers within a mafic layered body was observed at A-260-ML, 1700 feet north of A-299-ML. This mafic layered mass crops out in a northeast-southwest band on a steep, westward-dipping glaciated surface. The southern end of the body is hidden under talus. The sketch map of Figure 20 shows the relation between the layers at the northeastern limit of the exposure. Considering the north contact of the body as the trace of the lower surface, the lower beds form a small syncline which plunges to the southwest. The layering on the south limb of this syncline butts against the upper sequence of more steeply dipping mafic-rich layers. This is not a fault relation, however, because the upper sequence is made up of lens-like layers whose shape is related to the curved surface which separates the two sequences. The relations suggest that the upper sequence is filling a channel in the underlying layered sequence. This type of relation was not observed

Figure 18. Intrastratal faulting in mafic layered granodiorite. Lowest layer is not cut by faults.

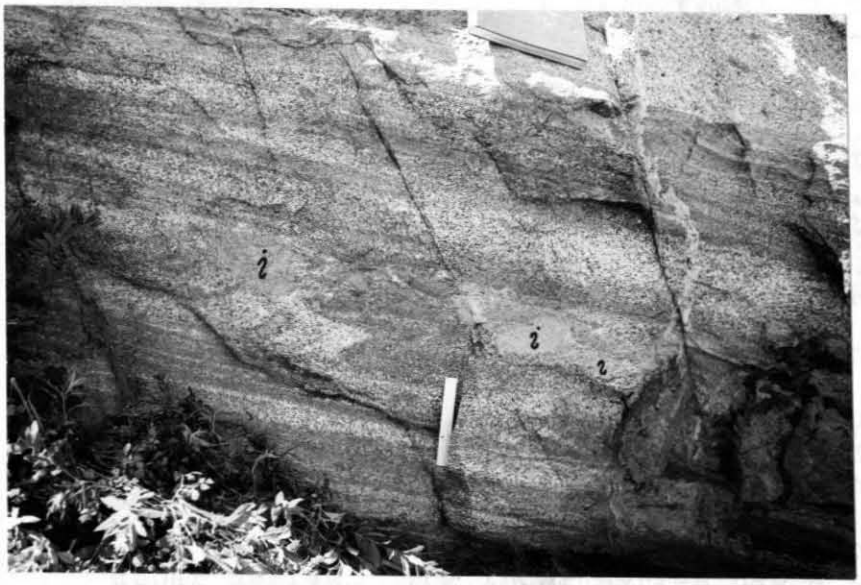


Figure 19. Intrastratal folding at A-299-ML. Folding is confined to 8-inch bed between undeformed mafic layers. Four fine-grained amphibolite inclusions (i) are found in the deformed layer. Scale is 6½ inches long.

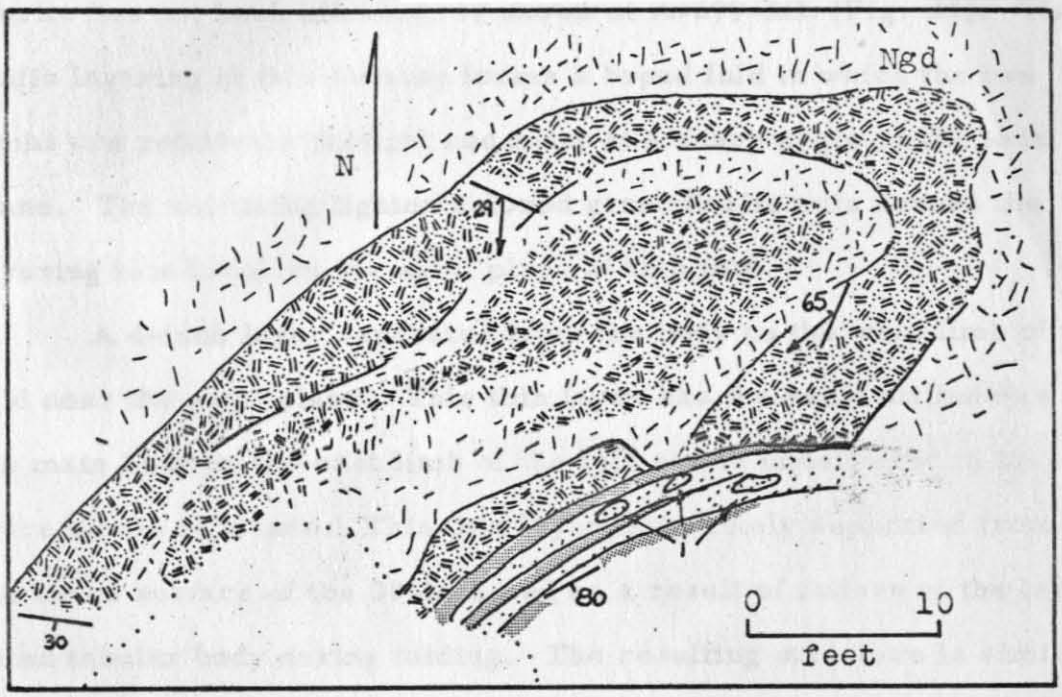


Figure 20. Sketch map of mafic layered granodiorite at A-260-ML, 3500 feet N. 60° W. of Mt. Wolverine. Lower series (dash-dot pattern) forms syncline which plunges to the southwest. Upper, more steeply dipping series (shaded pattern) truncates the south limb of this syncline, and is made up of lens-like layers whose shape is related to the curved surface which separates the two sequences. The individual layers in the upper series are 2 to 6 inches thick and are shown only diagramatically. Fine-grained amphibolite inclusions (i) are found in the upper series. The lower series has a sharp contact with the underlying nonporphyritic granodiorite (Ngd). The relation of the upper series to the nonporphyritic granodiorite is not known.

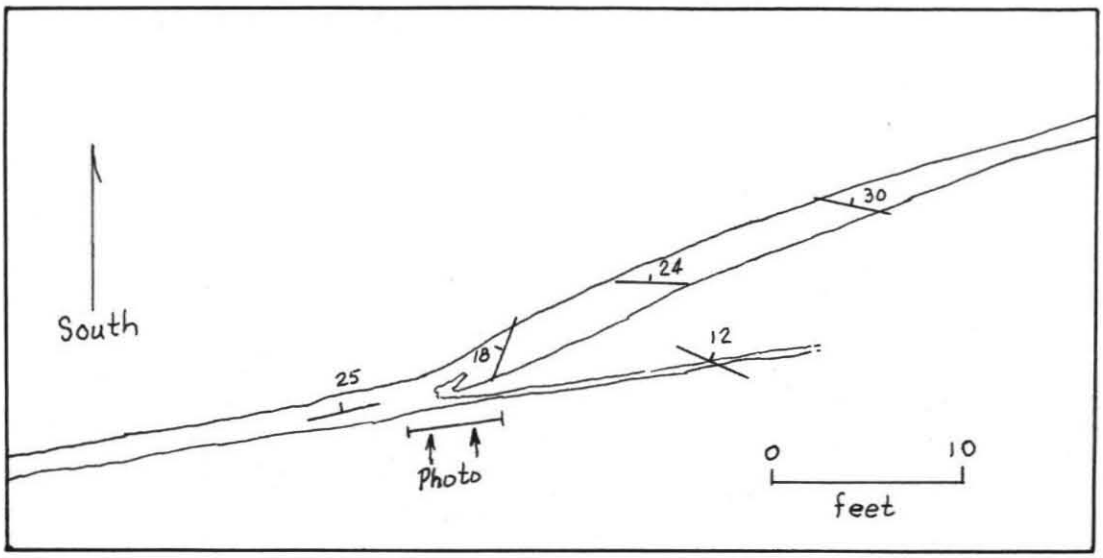
in any other mafic layered body.

A structure of the second type, in which the mafic layered granodiorite body has been folded as a unit but the enclosing granodiorite has not been affected, is shown at A-299-ML (Fig. 21). The mafic layering at this locality forms a broad fold in which the two limbs are relatively straight and meet at a sharp angle on the axial plane. The enclosing lighter colored granodiorite cuts across the layering in a break on the axial plane of this fold.

A 4-inch layer separates from the body on the west limb of the fold near the axial plane. This thin layer has the same attitude as the main body on the east limb of the fold and is undeflected in its trace on the cliff face. This thin layer most likely separated from the lower surface of the 30-inch bed as a result of failure of the laminated tabular body during folding. The resulting structure is similar to that produced by bending a sheet of plywood beyond the breaking point.

All the structural relations at A-299-ML which are illustrated in Figures 18, 19 and 21, indicate that the layering, folding and faulting of the mafic granodiorite was produced before the enclosing granodiorite was solid, and, therefore, the mafic layered granodiorite bodies are inclusions in the nonporphyritic granodiorite.

Post-solidification movements, structures of the third type, have produced faults and drag folds in the mafic layered granodiorite and in the enclosing lighter colored granodiorite (Fig. 22). Such movements may account for the termination of the mafic layering in some cases. The faults which cut the layering and the granodiorite



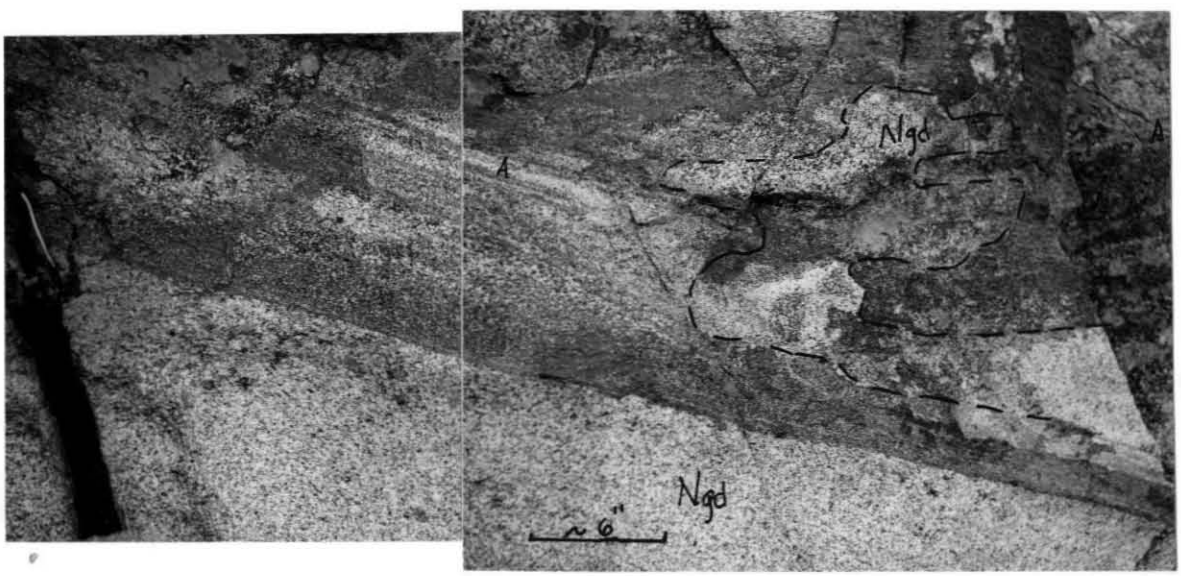
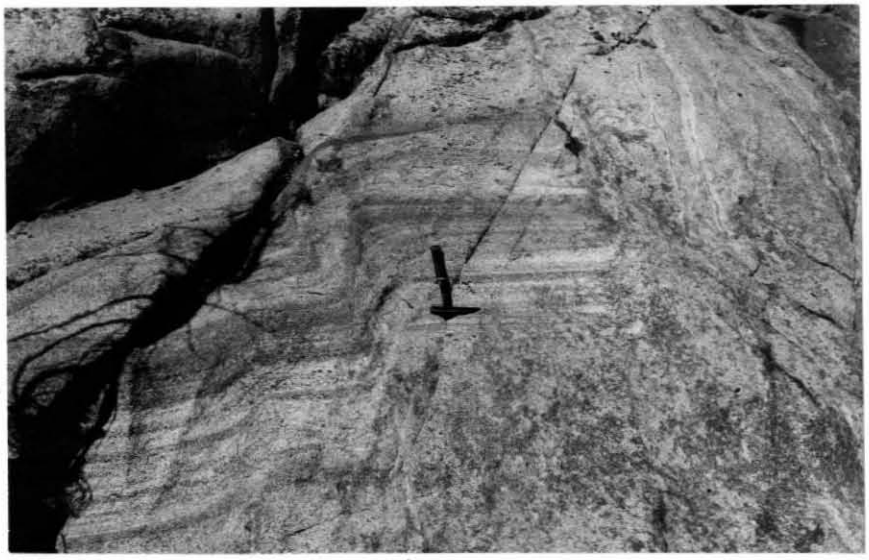
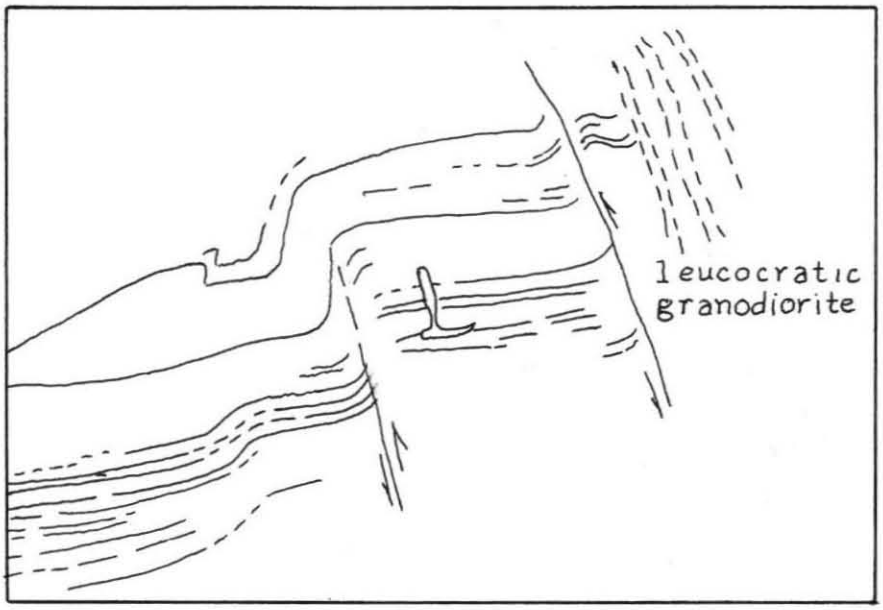


Figure 21. Rupture on axial plane of broad fold in mafic layered granodiorite at A-299-ML. Break in mafic layering is filled with nonporphyritic granodiorite (Ngd). Bed marked A can be traced across break.

A. Sketch map of field relations.
B. View of cliff face, looking south.



A.



B.

Figure 22. Post-solidification faulting of mafic layered granodiorite and enclosing nonporphyritic granodiorite at A-298-ML, 3700 feet N. 60° W. of Mt. Wolverine. Fault on left side of photograph changes upward into monocline. Zone of streaked leucocratic rock (on right) is at least 15 feet wide, and there is no trace of the faulted portion of the body.

A. Photograph looking east, hammer for scale.
B. Line drawing showing trace of faults.

commonly are accompanied by broad, poorly defined zones of leucocratic granodiorite which has a streaked character.

Composition and Texture

The mafic layered granodiorite contains the same minerals and inclusions as the enclosing nonporphyritic granodiorite, and the composition differs only in mineral proportions. The optical properties and textural relations of the minerals are also the same in the two types of granodiorite.

The plagioclase has oscillatory zoning and an average composition of An 35. The andesine cores of the plagioclase are euhedral, but the extensive oligoclase overgrowths are irregular in outline. In the slab of the mafic layering at A-299-ML which is shown in Figure 17, the textural parameter, Dp is 1.9 in the coarser grained layer of A-299-3 and 1.6 in the finer grained layer of A-299-4.

Hornblende, biotite and sphene form euhedral crystals which do not have overgrowths. Hornblende and sphene and to a lesser extent biotite, however, have embayments filled with oligoclase, quartz, orthoclase or magnetite. Quartz, orthoclase and the sodic rims on the plagioclase fill the interstitial space between the euhedral hornblende, biotite sphene and the andesine cores of the plagioclase. In addition, orthoclase forms rare poikilitic crystals up to 5 mm in diameter.

Approximately 10 percent of the biotite in the rock is found in hornblende crystals. Fifty percent of the magnetite in the rock is found in the larger crystals of hornblende, biotite and sphene.

Small, rounded, dark fine-grained inclusions similar to those

found elsewhere in the stock are common in the layered rocks. (Figs. 19 and 20).

Modal analyses were made of three samples collected at locality A-299-ML (Table 23): samples A-299-3 and A-299-4 which are shown in Figure 17, and A-255c-ML which is from a dark layer located 6 inches stratigraphically above the top of the layering shown in the slab in Figure 17A and 10 feet to the east. A-299-3-ML was taken from the coarser grained layer near the base of the slab, and A-299-4-ML was taken from the overlying finer grained layer. Both modes have the feldspar ratio and the quartz content of a granodiorite, but have 50 percent dark minerals, almost four times as much as the average nonporphyritic granodiorite, and twice as much as the average border rock. Considering the difference in average grain size, it is interesting to note the remarkable similarity between the two modes. Relative to the average border rock, the heavy minerals are 1.3 to 2.2 times more abundant in the mafic layered rocks.

The ratio of biotite+chlorite to biotite+chlorite+hornblende is 0.45 in the layered rocks and 0.45 in the border rocks, but 0.60 in the average nonporphyritic granodiorite. On the other hand, the ratio of quartz to orthoclase is 1.0 in the mafic layered granodiorite, and 1.05 in the nonporphyritic granodiorite, but 1.7 in the border rocks. These ratios suggest that the biotite and hornblende of the layered rocks crystallized from a magma of the same composition and physical conditions as the magma from which the border rocks crystallized and that the quartz and orthoclase crystallized later and were contemporaneous with the quartz and orthoclase of the

TABLE 23. MODAL ANALYSES OF MAFIC LAYERED GRANODIORITE

	volume %					
	A-255-L	A-299-3	A-299-4	Average	Average Border Rock	Average Nonpor. Gd.
Plagioclase	26.3	22.5	23.7	24.2	52.1	40.7
Plag alt min	3.0	3.2	3.3	3.2	7.2	5.15
Orthoclase	11.9	12.9	11.6	12.1	5.3	19.1
Quartz	13.6	9.1	13.4	12.0	9.1	19.6
Hornblende	18.2	24.6	21.7	21.5	12.3	6.0
Biotite	16.7	15.4	14.7	15.6	8.5	5.6
Magnetite	5.8	5.1	5.9	5.6	2.2	1.6
Apatite	1.0	1.1	1.3	1.1	0.8	0.5
Sphene	1.8	2.7	2.8	2.4	0.7	0.6
Chlorite	1.6	3.1	1.1	1.9	1.7	1.0
Zircon	--	0.1	0.1	} 0.3	0.2	0.15
Allanite	0.3	0.05	0.3			
Total	100.2	99.85	99.9	99.9	100.1	100.00
Count	1146	1971	1838			
S in C *	1.0	1.7	0.5			
B in H	--	1.6	0.5			
Mte in mafics	--	2.4	--			
Myrmekite	--	--	0.3			
B + C	18.3	18.5	15.8	17.5	10.2	6.6
Color index	44.4	49.95	46.5	47.3	25.6	13.9
Total plag	29.3	25.7	26.8	27.4	59.0	45.85
Other	0.3	0.15	0.4	0.3	0.2	0.15
$\frac{B + C}{B + C + H}$				0.45	0.45	0.60
$\frac{Quartz}{Orthoclase}$				1.0	1.7	1.05

*See Table 11 for abbreviations.

enclosing nonporphyritic granodiorite.

Origin

The similarities in mineralogy, grain-size distribution, mineral composition, and textural relations of the mafic layered granodiorite and the nonporphyritic granodiorite argues for crystallization of the constituent minerals of these two rocks from a common magma under similar conditions. The following features suggest the mafic layered granodiorites are gravity-controlled accumulations of early-formed intratelluric heavy minerals from the Alta magma.

1. The very high percentage of minerals with higher-than-average specific gravity.
2. The high percentage of euhedral crystals of the early crystallizing minerals hornblende, biotite, plagioclase and sphene.
3. The alternation of coarse-grained and fine-grained layers, and high-density and low-density layers.
4. The orientation of elongate grains parallel to the compositional layering.

The alternation of coarse-grained and fine-grained layers, and high density and low density layers suggests a sorting mechanism operated during the deposition of the mafic layered granodiorite. If the sorting is based on Stokes law, then the terminal settling velocity will vary as the square of the effective diameter of the mineral grain, and linearly with density difference between liquid and mineral. If the mafic-rich layer shown in Figure 17A is interpreted as a graded bed resulting from Stokes-law sorting, then on the basis of grain-size distribution in the specimen, the right side of the

slab as shown in the figure is up. This agrees with its orientation in the field. This size sorting is not limited to the mafic minerals in A-299-3 and 4. The plagioclase grains also decrease in size upward in the specimen.

The strong lineation in all specimens of the layered rock suggests deposition from moving currents. The texture of the rock rules out metamorphism for the origin of the planar and linear structure. The relations at A-260-ML (Fig. 20) can be interpreted as a scour-and-fill structure in which the earlier sequence was deformed before the later sequence was deposited. This interpretation is compatible with a hypothesis of deposition from moving currents.

The features of the mafic layered granodiorite can be explained by a two-part history. In the first part, the mafic layered granodiorite formed as a placer deposit in a lower part of the magma chamber. Early in the history of the Alta stock convection currents, descending along the walls of the magma chamber, carried growing crystals of hornblende, biotite, plagioclase, magnetite, sphene and apatite in roughly the same proportions as these minerals occur in the border rock. As the currents spread out on some lower surface in the magma chamber, the mineral grains began settling out of the magma according to relative size and density. The euhedral crystals came to rest with their longer dimensions parallel to the surface of accumulation. Fluctuations in current velocity and direction produced variations in the composition and size of the crystals accumulating at any given point.

After accumulation, the crystals principally of plagioclase continued to grow and because the grains were essentially in contact

with one another at the time of deposition, the mass of crystals became loosely cemented. During the time of accumulation slumping took place producing some of the intrastratal folding and faulting like that shown in Figures 18 and 19. These structures are similar to the disturbed rhythmic layering in the norite zone of the Stillwater complex described by Hess (1960, p. 130).

During the second stage in the history of the mafic layered granodiorites, the cumulate was broken up and large masses of it were moved an unknown distance by the magma. In the process of breaking the tabular masses loose from their original site of accumulation, minor folding and faulting disrupted the layering and magma, which later crystallized to the nonporphyritic granodiorite, intruded along and locally across the bedding. Judging from the post-accumulation structural behavior of these bodies, they must have had considerable tensile strength parallel to the layering. In some cases, injection of magma along the layering produced a patchy rock in which the layering is completely disaggregated.

The last structural event to affect the layering was late-stage faulting in which both the enclosing nonporphyritic granodiorite and the mafic layered granodiorite responded as a unit to the deformation.

Layered structures resulting from accumulation of crystals by gravity settling are commonly described in gabbros and ultramafic rocks, but documented examples of magmatic crystal accumulation in more acidic rocks are rare. Harry and Emelius (1960) describe mineral layering in the upper parts of flourite-bearing biotite-granites of southwest Greenland. However, the classic

studies of the Skaergaard and Stillwater intrusions(Wager and Deer, 1939; Hess, 1960) provide the basis for understanding similar structures in more complex structural settings.

Wager et al. (1960) have presented a genetic classification of cumulates based on the "ways of completing the crystallization process". The textural relations of the mafic layered granodiorite indicate it is an orthocumulate which is defined as "a cumulate consisting essentially of one or more cumulus minerals together with the products of crystallization of the intercumulus liquid, which necessarily has the composition of the contemporary magma".

Poldervaart and Taubeneck (1959, p. 1395) propose a subdivision of rhythmic layering into: (1) layering of the Skaergaard type and (2) layering of the Willow Lake type. In Skaergaard-type layering, the crystals of the constituent minerals show a preferred orientation of their longer axes in the plane of banding. The layering is due to crystal sedimentation under the influence of gravity, accompanied and rendered repetitious by periodic disturbances in the magma. The mafic layered granodiorite is a cumulate of the Skaergaard type. In Willow Lake-type layering the crystals of the constituent minerals are arranged with their longer axes at high angles to the layering. The crystals are commonly elongate, curved and branching. "The layering is due to undercooling and crystallization in the oversaturated region, combined with periodic disturbances in the magma."

ALTA STOCK IN THE SCOTTS PASS AREA

Distribution and Contact Relations

The geology of the northeastern part of the Alta stock is shown in Figure 23. Most of the granodiorite in this area contains more orthoclase than the granodiorite in the rest of the stock, and is called quartz monzonite. A gradational contact presumably exists between the quartz monzonite and the granodiorite of the main part of the stock. The contact with the Clayton Peak diorite is not exposed in this area. The contact with the sedimentary rocks on the north is also largely covered, but at Scotts Pass the contact is exposed and the quartz monzonite intrudes the Ankareh formation (Triassic). Dark greenish gray, highly altered, diorite porphyry dikes up to 30 feet wide intrude the quartz monzonite. The dikes have a chill zone against the quartz monzonite host rock. Unpublished geologic maps of the United Park City Mines Company show that mine workings on the 900 level of the Thaynes mine intersect similar diorite porphyry dikes 2000 feet below the surface west and north of Shadow Lake.

Composition and Texture

The Alta stock in the Scotts Pass area is composed of medium-grained, medium-gray quartz monzonite and is distinguished from the normal granodiorite by the generally darker color and the lack of prominent hornblende crystals. In weathered specimens of the rock white plagioclase crystals 2 to 3 mm across stand out in a dark matrix of quartz, orthoclase, biotite and hornblende which has an average grain size only slightly smaller than the average size of the plagioclase crystals. Weathering accentuates the difference in color between the plagioclase and the matrix, but in thin section it is clear

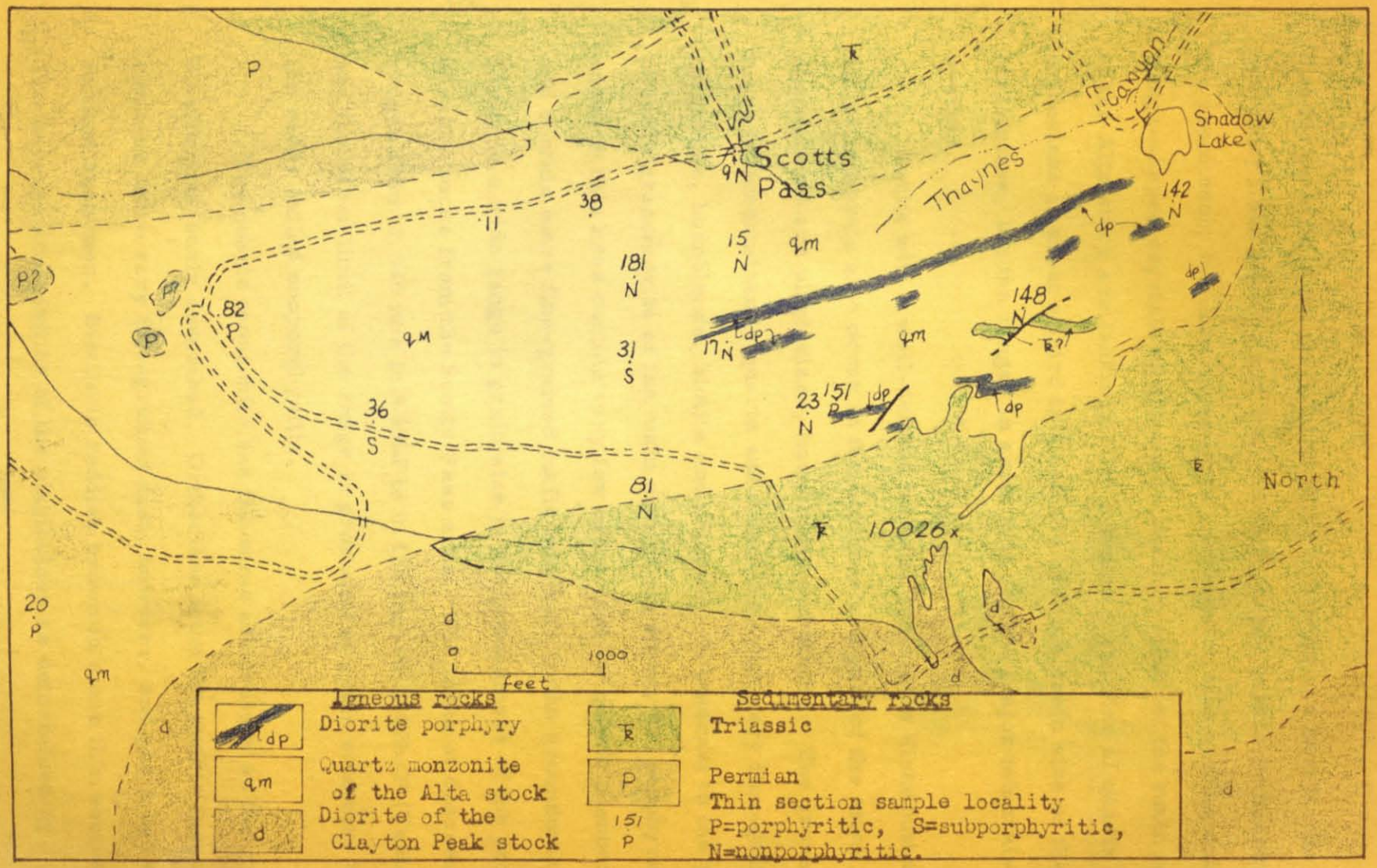


Figure 23. Geology of the Alta stock in the Scotts Pass area. Scale: 1000 feet to the inch. Geology modified by J.C. Wilson from Boutwell (1913 and 1923), and Calkins and Butler (1943).

that the texture is not truly porphyritic. Biotite and hornblende are generally finer grained and less euhedral in the quartz monzonite and the prominent, but uncommon large hornblende laths and the euhedral, wedge-shaped crystals of sphene so characteristic of the main mass of the Alta stock are lacking. The average grain size of quartz and orthoclase is about a third to a half the average grain size of the plagioclase, but the ranges in grain size for the major minerals overlap.

Rocks with a well-defined bimodal grain-size distribution of major minerals also occur in the northeastern part of the stock. The phenocrysts are plagioclase, hornblende and biotite. The groundmass is predominantly quartz and orthoclase with very fine-grained magnetite, hornblende, biotite and chlorite. In contrast to the porphyritic granodiorite of the main part of the stock, the porphyritic rocks in this area contain very few orthoclase or quartz phenocrysts and contain more fine-grained mafic minerals in the groundmass. There is a wide range in grain size in the groundmass of the porphyritic rocks from the Scotts Pass area. The index of coarseness ranges from 0.045 mm in A-151-P to 0.160 mm in A-82b-P (Table 21), and the upper limit of the range in groundmass grain size may be in the rocks called nonporphyritic.

The quartz monzonite has the same mineralogy as the granodiorite previously described. Orthoclase from the quartz monzonite contains more very fine-grained dust, however, and has a red color in hand specimen. Biotite is reddish brown in some thin sections. The average composition of the plagioclase as determined by

TABLE 24. MODAL ANALYSES OF ROCKS OF THE ALTA STOCK IN THE SCOTTS PASS AREA

volume %

	Nonporphyritic					Porphyritic			
	A-9	A-15	A-17	A-23	Average	A-11	A-82	A-151	Average
Plagioclase	37.2	28.2	32.0	50.9	} 39.5	39.4	40.0	36.3	} 41.4
Plag alt min	0.4	3.1	2.2	4.2		5.8	2.5	0.2	
Orthoclase	28.0	25.5	22.0	14.5	22.5	27.2	22.9	25.6	24.9
Quartz	13.8	15.8	18.7	11.7	15.0	14.7	21.3	18.9	18.3
Hornblende	13.8	19.8	14.8	10.2	14.6	4.9	5.8	9.0	6.6
Biotite	4.2	3.6	5.7	5.3	4.7	2.9	4.6	5.2	4.2
Magnetite	1.5	2.5	2.4	2.1	2.1	2.5	1.6	2.2	2.1
Apatite	0.3	0.4	0.4	0.4	0.4	0.4	0.2	0.1	0.2
Sphene	0.4	0.3	1.7	0.2	0.7	1.6	--	0.8	0.8
Chlorite	0.3	0.8	0.4	0.4	0.5	0.8	0.3	1.5	0.9
Zircon	--	--	--	0.1		--	--	--	} 0.2
Unknown	--	0.1	--	--		--	0.8	--	
Total	99.9	100.1	100.3	100.0	100.0	100.2	100.0	99.8	99.6
Count	1554	945	1651	1704		512	1836	1102	
Phenocrysts									
Plagioclase						--	38.6	34.1	
Orthoclase						--	0.6	--	
Quartz						--	0.7	--	
Groundmass						41.9	44.3	46.6	
Plagioclase						--	1.4	2.2	
Orthoclase						--	22.3	25.5	
Quartz						--	20.6	18.9	
K in plag.*	--	--	--	0.2		--	--	0.1	
B in plag.	--	--	--	0.1		--	--	--	
B in H	--	--	--	0.1		--	0.2	--	
S in C	--	--	--	--		--	0.5	--	
B + C	4.5	4.4	6.1	5.7		3.7	4.9	6.7	
Color index	20.2	27.8	25.4	18.2		12.7	13.1	18.7	
Total plag.	37.6	31.3	34.2	55.1	39.5	45.2	42.5	36.5	41.4
Other	--	0.1	--	0.1		--	0.8	--	0.2

*See Table 11 for abbreviations.

measuring extinction angles in five thin sections is An 38. The plagioclase of A-82-P has An 15 overgrowths.

The average modal composition of four nonporphyritic and three porphyritic rocks from this area, Table 24, is that of a quartz monzonite but only by virtue of a few percentage points more of orthoclase than the granodiorite. Compared to the main mass of granodiorite, the average quartz monzonite contains less quartz and total plagioclase, and more orthoclase and hornblende. Within the Scotts Pass area of the Alta stock, the porphyritic rocks contain more orthoclase and quartz, and less hornblende than the nonporphyritic rocks. The abundance of biotite + chlorite is the same in the two textural types of quartz monzonite. These are the same compositional relations shown by the two major textural types of granodiorite.

Because of the poor exposures and extensive deep weathering, the relations between textural types of quartz monzonite in this area could not be determined.

DIKE ROCKS

Leucocratic quartz monzonite

Distribution and Contact Relations. Light-gray medium-grained leucocratic quartz monzonite dikes ranging in thickness from 2 to 15 inches, cut all phases of the Alta granodiorite. They are common and well exposed on the glaciated cliffs between Brighton and Lake Mary, and in general have a spatial affinity to the periphery of the porphyritic granodiorite. The dikes are similar in color and texture to the host rock, but are distinguished from the granodiorite by their slightly lighter color and by the presence of small segregations of dark-colored

minerals. The contacts of the dikes are generally straight, sharp and well defined, as is shown in Figures 24 and 25. The contacts are marked by a slight difference in color index but not by an abrupt difference in mineralogy or crystal size. In several locations however, the dike rock near the contact contains a high abundance of dark minerals and has a layered appearance (Fig. 24). The contacts are also the loci of small aplite dikes.

The attitudes of the leucocratic quartz monzonite dikes are highly variable. The attitude may be constant for 10 feet, make a sharp change in strike and then be constant for a similar distance in another direction. In a few cases the dikes terminate by an abrupt jog accompanied by a decrease in thickness, but generally they disappear by a darkening in color along the trace without apparent thinning until the dike rock can not be distinguished from the enclosing granodiorite. Because of the complex relations and similarity in appearance to the host rock, the dikes can be mapped adequately only on a detailed basis.

Composition and texture. Plagioclase, orthoclase and quartz are the principal minerals of the leucocratic quartz monzonite dikes. The central parts of the plagioclase grains have a composition of An 38, but extensive rims of An 25 give the plagioclase in these dikes an average composition which is more sodic than the plagioclase in the granodiorite. "Sericite" is common in the plagioclase. The major dark mineral in the leucocratic part of the dikes is chlorite which forms pseudomorphs after biotite. Magnetite, sphene, hornblende, apatite and hematite are also found in the dikes. No pyrite was seen in these dikes. The biotite and hornblende have the same pleochroism and indices as the corresponding minerals in the granodiorite.

Figure 24. Segregation of mafic minerals in leucocratic quartz monzonite dike at A-211-L, 1200 feet N. 10° W. of Lake Mary. Photograph taken down 48° dip. Field relations are sketched at right. Lower contact of mafic segregation is sharper than upper contact. Aplite dikelet follows upper contact; thin dark selvage marks lower contact.

Figure 25. Leucocratic quartz monzonite dike cutting large amphibolite inclusion in porphyritic granodiorite. Vertical dip. Photograph taken toward south. Location 200 feet north of dike shown in Figure 24. Dike can be mapped easily in and below inclusions but is more difficult to map in the area above the inclusion because it contains nearly as many dark minerals as the enclosing granodiorite.

The segregations of dark minerals are the most striking feature of the leucocratic quartz monzonite dikes. The color index of the segregations is approximately 40 percent. They contain abundant chloritized biotite, hornblende, sphene and magnetite. The hornblende laths have a planar orientation parallel to the contacts of the segregations. The mafic segregations have both sharp and gradational contacts. In dikes that dip less than 45 degrees the gradational contacts are generally on the top side of the segregations (Fig. 24).

The average modal composition of two thin sections from different dikes, is that of a quartz monzonite with only 3.5 percent dark-colored minerals (Table 25). No attempt was made to determine the modal composition of the mafic segregations, or to determine the relative proportions of the leucocratic and melanocratic material in the dikes. Consequently, the average modal composition given in Table 25 is not representative of the total composition of these dikes. No thin sections were made of the mafic segregations but the abundance of biotite appears to be very much greater than the abundance of hornblende.

The texture of the leucocratic quartz monzonite dikes is subporphyritic. The index of coarseness of A-219-L, 350 feet northeast of Lake Mary, is 0.27 mm. Subhedral crystals of plagioclase range in size from 1 to 5 mm. Euhedral to subhedral crystals of sphene and chloritized biotite have an average grain size of one mm. Corroded, euhedral lath-shaped crystals of hornblende range in length from 1 to 6 mm. Some of the quartz and orthoclase is in

TABLE 25. MODAL ANALYSES OF QUARTZ MONZONITE DIKES IN THE ALTA STOCK

volume %

	A-215	A-219	Average
Plagioclase	36.8	39.4	38.1
Plag alt min	3.0	2.9	3.0
Orthoclase	26.2	26.5	26.4
Quartz	29.6	27.4	28.5
Hornblende	--	0.1	--
Biotite	0.1	0.8	0.4
Magnetite	0.5	0.5	0.5
Apatite	0.2	0.2	0.2
Sphene	0.4	0.2	0.3
Chlorite	3.2	1.9	2.6
Zircon	0.1	--	} 0.1
Hematite	--	0.1	
Total	100.1	100.0	100.2
Count	1712	1708	1710
K in plag.*	0.4	0.8	--
B + C	3.3	2.7	3.0
Color Index	4.2	3.6	3.9
Total plag.	39.8	42.3	41.1
Other	0.1	0.2	0.1

*See Table 11 for abbreviations.

1 mm subrounded grains, but most is in the relatively coarse-grained groundmass. The groundmass has a composition and crystal size similar to that of the aplite dikes.

Aplite-pegmatite Dikes

Distribution and contact relations. Fine-grained aplite dikes, commonly with pegmatitic cores, cut all other rock types of the Alta igneous suite, including the quartz monzonite dikes. Aplite dikes are more common in the border phase of the stock and are especially abundant and well exposed on the north shore of Twin Lakes reservoir. At A-309-N and other localities in the southern part of the stock, aplite dikes are localized in part on the strong radial joint set in the nonporphyritic granodiorite and in some cases are cut off by the contact of the later porphyritic granodiorite (Fig. 3). Aplite dikes are very rare in the porphyritic granodiorite, and those that were seen are generally associated with the quartz monzonite dikes (Fig. 24). The dikes have sharp contacts and in many cases cleave readily from the enclosing granodiorite. Pegmatitic crystals up to two cm in maximum dimension occur in cavities in the center of the larger dikes.

Composition and texture. Orthoclase, quartz and plagioclase are the major minerals of the aplite-pegmatite dikes. The orthoclase is coarsely perthitic in the pegmatitic core, containing up to 15 percent visible albite lamellae. The orthoclase in the aplitic margins shows weak, practically non-existent perthitic texture. Plagioclase has a composition of An 15 in A-107-AP and shows no optical zoning in either the aplitic or the pegmatitic portions of the dikes. The usual accessory minerals in the aplite are biotite, chlorite and hematite,

although sphene, epidote, pyrite, and muscovite have also been seen.

The vugs in the pegmatitic cores of the dikes contain euhedral crystals of pink orthoclase, white albite, and gray quartz with much rarer brown wedges of sphene, green tufts of epidote, and brown hematite, pseudomorphic after pyrite. Biotite flakes were seen in the pegmatite cores of the dikes but no biotite books were found in the vugs.

The composition of the aplite-pegmatite dikes is uniform within the stock. The average modal composition of four dikes has the quartz content and feldspar ratio of a quartz monzonite (Table 26). Three of the four modes used in the average are from fine-grained parts of the dikes having aplitic or micrographic texture. The fourth mode is from the coarse-grained, micrographic textured rock near the center of an aplite-pegmatite dike at A-232-AP. The orthoclase in this rock is unusual in that it is strongly perthitic. This rock appears to have the same modal composition as the three finer grained aplitic rocks if the abundance of the exsolved albite lamellae is added to the abundance of the very coarse grained oligoclase.

For comparison, the average composition of the groundmass of the porphyritic granodiorite is given in column A of Table 26. The aplite dikes have the same quartz-orthoclase ratio as the groundmass of the porphyritic rocks. If the oligoclase overgrowths on the plagioclase phenocrysts in the porphyritic granodiorite are considered contemporaneous with the groundmass, then the groundmass (col. B, Table 26) of the porphyritic rocks has a modal composition which is very similar to the average modal composition of the aplite-pegmatite dikes.

TABLE 26. MODAL ANALYSES OF APLITE-PEGMATITE DIKES

volume %

	A-92	A-107	A-198	A-232	Average	Groundmass of porphyritic granodiorites	
						A	B
Plagioclase	21.8	} 19.2	19.1	} 21.6	} 21.2	} 8.5	27.6
Plag alt min	2.8		0.2				
Orthoclase	39.0	45.5	40.3	41.7	41.6	49.0	39.0
Quartz	35.4	34.7	39.4	35.2	36.2	42.5	33.4
Biotite	--	0.1	0.2	0.5			
Sphene	--	--	0.2	--			
Chlorite	0.3	0.1	0.1	0.2			
Zircon	--	--	--	--	1.0		
Hematite	0.2	0.1	0.5	0.3			
Muscovite	--	--	--	0.1			
Myrmekite	0.5	0.2	--	0.4			
Total	100.0	99.9	100.0	100.0	100.0	100.0	
Count	1001	1386	1698	1726			
Plag. lamellae in orthoclase	--	0.2	--	7.6			
B + C	0.3	0.2	0.3	0.7	0.4		
Color index	0.5	0.3	1.0	1.0	0.7		
Total Plag.	24.6	19.2	19.3	21.6	21.2		
Other	0.7	0.3	0.5	0.8	0.6		
$\frac{\text{Quartz}}{\text{Orthoclase}}$					0.87	0.87	0.87

column

A See Table 13.

B 27.85% of col. A added to 7.3% of plagioclase overgrowths and the sum equated to 100%. See Table 12 and p. 37.

The change from aplitic margin to pegmatitic core in these dikes takes place by a change in texture from fine-grained allotriomorphic granular at the wall to coarse-grained panidiomorphic granular in the core. In some dikes this change is abrupt, but commonly this change is effected by a gradual increase in grain size accompanied by the development of an intermediate micrographic texture. The aplitic and micrographic portions of A-107-AP are shown in Figure 26.

Gradations in modal composition accompany the gradations in texture within the aplite-pegmatite dikes. Modal analysis of thin section A-198-AP, 500 feet south of Mt. Wolverine, illustrates this change. The thin-section is oriented perpendicular to the wall of a four-inch dike. The texture is fine-grained, granular on the wall-rock side of this thin section and becomes gradually micrographic and coarser grained toward the other side of the thin section, which is the center of the dike. The modal analysis of this thin section began on the wall-rock side of the section with traverses parallel to the wall and progressed toward the center. The cumulative totals were recorded at three intervals and the modal composition of the three areas is recorded in Table 27. Orthoclase and quartz are more abundant in the coarse-grained, micrographic-textured inner part of the dike than in the aplitic-textured outer part.

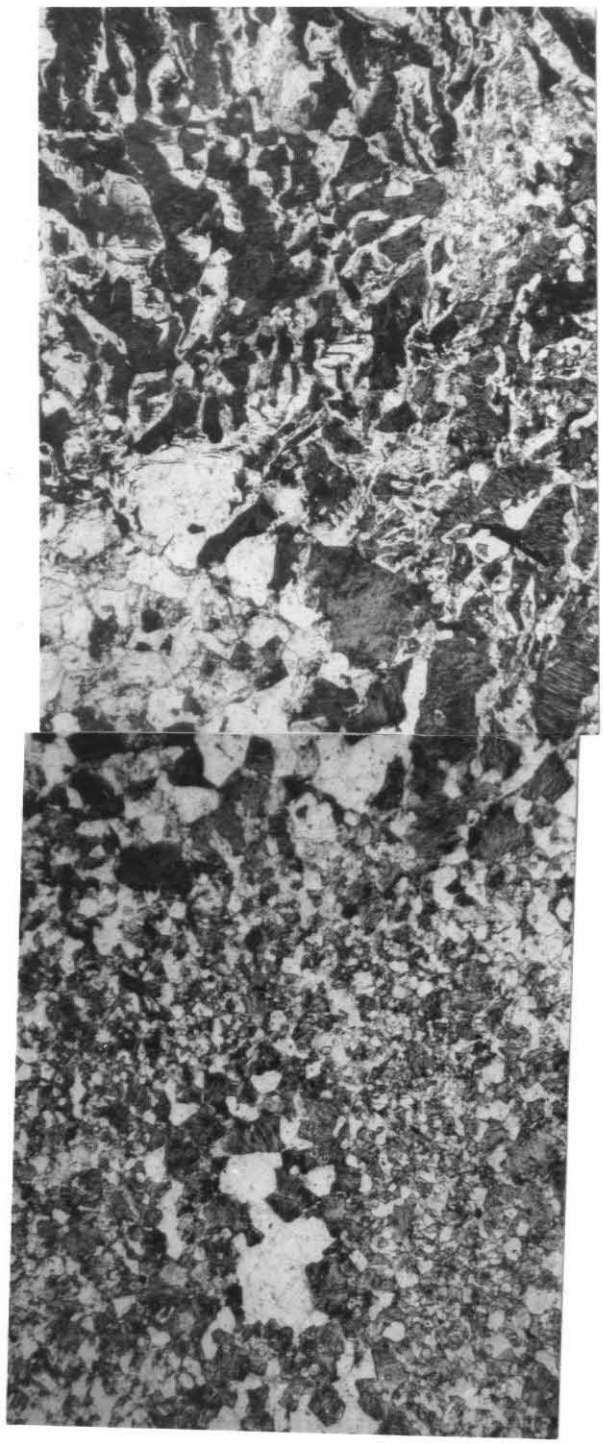


Figure 26. Aplitic and micrographic portions of dike, A-107-AP, located 1500 feet S. 45° W. from Mt. Wolverine. Aplitic textured part in lower half of view is nearest the wall, micrographic part in upper half is toward the pegmatitic center of the dike. Dark gray is stained orthoclase, medium gray is oligoclase, and light gray is quartz. Plane light, x10.

TABLE 27

MODAL ANALYSIS OF A-198-AP

volume %

	wall		center	
	1	2	3	Total
Plag. plag. alt. min.	24	19.5	16	19.4
Orthoclase	38	44.5	40	40.6
Quartz	36	36.0	44	40.0
	100	100.0	100	100.0
Points	492	489	699	1680

Origin. The localization of the aplite dikes on joints which are older than the porphyritic granodiorite, the general lack of these dikes in the central part of the stock, and the cross-cutting relation at A-309-N on the east shore of Lake Mary, suggest that the aplite-pegmatite dikes are older than the intrusion and solidification of the porphyritic granodiorite. The similarity in average modal composition of the aplite dike to the adjusted modal composition of the groundmass of the porphyritic granodiorite, suggests that the dikes could be a liquid extract of the phase of the Alta magma which is represented now by the porphyritic granodiorite.

The aplite-pegmatite dikes probably do not represent a single event in the cooling history of the magma. Aplitic differentiates were most likely generated at several times and possibly continuously during the crystallization history of the Alta magma. However the field evidence indicates that many of the dikes were intruded before or during the emplacement of the later phase of the magma.

Hornblende Joint Fillings

Coarse-grained hornblende with finer grained pyrite, sphene, and epidote is found on joint surfaces of all textural varieties of Alta granodiorite. The location and orientation of these mineral-filled joints is shown on Plate 4. Commonly the joint fillings are represented by local iron staining and sparse 1-cm hornblende crystals which give the joint surface a color index of 30 to 50 percent. The hornblende crystals are oriented with the long axes parallel to the joint surface. East of Lake Mary, however, the joint fillings are very well developed and form veinlets of hornblendite on the N. 25° W. joint set. At location A-365-H 400 feet east of Dog Lake, the joint fillings are up to one cm thick (Figure 27). Generally however, the introduced material is only a surface coating on the joints and on the average is much less than one mm thick.

The thicker fillings are accompanied by a bleached zone in which the percentage of orthoclase and quartz is higher than in the adjacent rock, biotite has altered to chlorite and magnetite is replaced by pyrite and hematite. Hornblende is found only in the joint fillings and does not extend into the bleached zone. East of Dog Lake, the N. 25° W. joint set is the locus for both aplite dikes and the hornblende joint fillings. In a few places, the aplite dikes cut across the hornblende veinlets and contain fragments of the hornblende crystals, but in other areas, conflicting age relations were seen. At A-92-AP at the north end of Twin Lakes reservoir dam, joint surfaces in thick aplite-pegmatite dikes are smeared with fine-grained hornblende.

Figure 27. Unusual hornblendite veinlet at A-365-H, 400 feet east of Dog Lake. View looking perpendicular to the plane of steeply dipping, N.25°W. 1-cm thick veinlet, the plane of the veinlet is nearly parallel to the plane of the photograph. The trace of the veinlet is shown in the lower part of the photograph. Hornblende crystals up to 10 cm long and sphene crystals up to 2 cm are present, but sphene is not visible in this view. The veinlets in this area are coarser grained and thicker than in any other area.

Individual hornblende crystals up to ten cm in length are common in the joint fillings as thin as 0.5 cm. Sphene crystals up to one cm in greatest dimension are common in the dikelets at A-365-H. Judging by the density of iron stain on joint surfaces, the abundance of pyrite is not high, nor is its distribution uniform.

The pleochroic formula of the hornblende is α=light yellowish green, β = yellowish green, and γ = blue green. The 2V is 60°. Hornblende from the veinlets is more fibrous than the hornblende from the granodiorite, and has partly altered to a fine-grained reddish brown mineral, probably biotite.

ALBION BASIN PEGMATITE

The Albion Basin pegmatite pod is located at A-102-AP on the east side of Albion Basin, 400 feet south of the Alta granodiorite contact. It is a concordant intrusion into the Middle Cambrian Ophir formation. The pegmatite is 30 feet thick and at least 200 feet long in a north-south direction. The pod dips 25° to the northeast with the enclosing metamorphosed Ophir shale. The pegmatite consists of coarse-grained micrographic granite, fine-grained aplite and very coarse-grained pegmatite. There is a gradation in texture between the aplite and the granite. The minerals of the pegmatite are orthoclase, quartz and sodic plagioclase with accessory biotite and hematite. The modal composition of an aplite dike connected to the upper contact of the pod (A-108-AP) is 65 percent orthoclase, 28 percent quartz, 5.3 percent sodic plagioclase and 1.7 percent accessory minerals. This mode has a considerably higher ratio of orthoclase to plagioclase than the four

modes of aplites from within the stock (Table 26).

The pegmatite has a layered appearance due to the stratification of textural types. There are many alternations in texture vertically within the pod, but only two pegmatitic zones were seen in a traverse down the cliff on which the pod is exposed. These layers occur near the center of the pod, are 1 and 3 feet thick, and contain crystals of quartz and orthoclase up to 12 inches long.

CRYSTALLIZATION HISTORY

Crystallization History Deduced from Field and Petrographic Relations

The general relations shown on the map of the area by Calkins and Butler (1943) suggest the sedimentary rocks were both folded and faulted in order to make room for the Alta magma. Although not included as an integral part of this study, certain observations on the relation of the granodiorite to the intruded sediments support this hypothesis. The contact of granodiorite against the host rock is generally sharp, inclusions are not abundant, and assimilation was probably a minor process in the emplacement of the magma. Thrust faults and bedding in the sedimentary rocks are folded about axes parallel to the contacts. The Alta stock is on the upthrown side of faults which strike parallel to the contacts.

The best estimate on the depth of the Alta stock during crystallization is based on stratigraphic evidence. The upper Cretaceous Frontier formation was the last formation to be deposited in the area before the Tertiary folding along the Uinta Arch. The main mass of the Alta stock west of Brighton intrudes the Deseret Formation (Mississippian). The minimum stratigraphic thickness of the Deseret formation through Frontier formation inclusive, is 20,500 feet (Crittenden et al. 1952), based on measurements in the Parley's Canyon syncline north of the Alta stock. Because there may have been thinning of the pre-Tertiary formations over the ancestral structure of the Uinta Arch, the figure of 20,500 feet should be regarded as a maximum. On the other hand, the pre-intrusive thrust faults may have caused repetition of units over the

Alta stock which could produce an effective cover greater than the estimated stratigraphic thickness.

Assuming an average density of 2.7, the stratigraphic thickness of 20,500 feet is equivalent to a rock pressure of 1700 kg/cm^2. In subsequent discussion it will be assumed that the total pressure during crystallization of the Alta stock was equivalent to this lithostatic pressure.

The emplacement of the Alta magma could have been a single event or a series of pulses spread over a significant fraction of the cooling history of the magma. The complex structural history of the mafic layered granodiorite and the intrusive relations of the porphyritic granodiorite indicate that movements did take place in the magma chamber, but whether these movements supplied new magma from a distant reservoir is not known.

The idiomorphic character of many of the crystals shows that much of the texture of these rocks was produced by growth of crystals which could move freely in a liquid and relatively little of the texture can be attributed to recrystallization and adjustment of grain boundaries after the rock was essentially solid.

Optical zoning in the feldspars of the granodiorite indicates that equilibrium was approached only between the surface of the growing feldspar crystals and the residual liquid. The earlier formed parts of the feldspar crystals were insulated from the liquid. The lack of zoning in biotite and hornblende may indicate either the lack of dependence of optical properties on the composition of these minerals, or that the

composition is uniform throughout individual crystals. Reaction minerals do not have a zonal arrangement in the hornblende. In contrast to crystallization of the feldspars, all parts of a hornblende crystal may have taken part in reaction with the liquid.

Crystals of plagioclase, hornblende and probably biotite were growing in all parts of the magma chamber, in the early part of the crystallization history of the Alta stock, but crystals of these minerals were much more abundant and were growing faster in the border zone than in the center of the stock. For some time after emplacement of the magma, crystals of the early-forming minerals could move freely in the magma with respect to one another. During this early stage, cooler heavier magma, which contained rapidly growing crystals of hornblende, biotite and plagioclase, moved down along the walls of the magma chamber. The mafic layered granodiorite is a placer accumulation of early-forming crystals from such a circulating magma.

As crystallization continued, the abundance of crystals in the border zone became so great that it prevented free movement of mineral grains, and the magma near the contact became a semirigid crystal mush. Plagioclase, biotite and possibly hornblende continued to crystallize from the interstitial liquid, resulting in mutually interfering boundaries for these three minerals. This interstitial liquid was in communication with the more mobile interior of the stock. Material for the growing crystals of the stable minerals was being continuously supplied to the interstitial liquid in the border rock, and the constituents in excess of the proportions entering growing crystals were being

transported toward the center of the stock. Crystallization of biotite, hornblende and plagioclase ceased in the border rock when the decreased permeability no longer permitted transport of material in and out of the pore liquid of the border rocks. The border rock was almost entirely solid when the temperature at the contact had decreased to the point where quartz and orthoclase began to crystallize from the interstitial liquid, forming irregular anhedral grains by replacement of earlier minerals. In some rocks these late minerals form grains which have optical continuity over an average space almost as large as the average space occupied by grains of plagioclase, hornblende or biotite.

While the border rock formed, a shell of partially to completely crystallized rock surrounded a more liquid mobile core in the Alta stock. At any time in this stage of crystallization, there was a complete gradation in the percentage of liquid in the magma from near zero in the border rock to 45 to 80 percent in the center of the stock. As the semirigid crystal mush increased in thickness toward the center of the magma chamber, the relative abundance of minerals crystallizing to form the phenocryst assemblage changed. The abundance of biotite and hornblende decreased and the abundance of plagioclase increased inward from the contact. In addition, the abundance of quartz and orthoclase, which crystallized from the interstitial liquid, increased greatly inward from the contact. Rare movements in the crystal mush produced the schlieren structure seen in the granodiorite within 1000 feet of the contacts. Movement in the central part of the stock brought displaced masses of the mafic layered granodiorite to their present position.

Quartz and orthoclase began crystallizing relatively early in the still mobile magma in the interior of the stock after most of the magma which crystallized to a nonporphyritic texture had become a semirigid crystal mush. Continued crystallization of plagioclase, orthoclase and quartz inhibited further relative movement of crystals, even in the center of the stock.

At a late stage in the crystallization history, the Alta stock had a completely solid shell of nonporphyritic granodiorite at least 1200 feet thick which surrounded the partially liquid but semirigid crystal mush in the central part of the stock. Structural adjustments at this late stage resulted in closely-spaced joints in the nonporphyritic granodiorite. Aplite dikes were in part intruded along these joints.

After the emplacement of the aplite dikes but before the interstitial liquid of the magma at the center of the stock had completely crystallized, the semirigid crystal mush was intruded by the later phase of the magma which formed the porphyritic granodiorite. The lateral extent of the partially liquid core of the stock at the time of this later intrusion is roughly equivalent to the distribution of subporphyritic textured rock on Plate 2. Good intrusive relations were produced only in parts of the stock where the later phase of the magma came in contact with the nonporphyritic granodiorite.

Most of the aplite-pegmatite dikes in the nonporphyritic granodiorite represent liquid extracts of the late-stage differentiate of the stock. The part of the interstitial liquid of the later phase of the magma which formed aplites may have been separated from its associated phenocrysts by a process of filter pressing in which the semirigid crystal

mush, which later formed the subporphyritic granodiorite, acted as the filter.

Intrusion of the later phase of the magma caused a change in the conditions affecting the further crystallization of the remaining liquid in both the crystal mush and in the phase of the magma which crystallized with a strongly porphyritic texture. Loss of volatiles through fractures in the overlying material caused the later phase of the magma to be locally oversaturated with respect to the silicate phases. The effect of the loss of volatiles was less pronounced on the magma which was farther from the fractures. Crystallization in both the liquid part of the later intrusive phase of the magma and in the residual interstitial liquid in the crystal mush was affected by this change in conditions.

The last rocks to solidify in the Alta stock were the leucocratic quartz monzonite dikes. They may have been derived from a late-stage phase of the magma by the same process as the aplite dikes with the exception that the filtering was less complete.

The age of the Albion Basin pegmatite to the other phases of the Alta igneous suite is unknown. However, its location and orientation suggest that it is probably the same age as the aplite-pegmatite dikes which cut the border rocks in the stock 400 feet to the north.

Crystallization in the Light of Experimental and Inferred Phase Equilibria Information

In this section the differentiation trends in the Alta igneous suite will be discussed in terms of the theoretical crystallization of a granodiorite magma in the system $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O (An-Ab-Or-SiO_2-H_2O).

Campbell (1959) constructed a schematic diagram of the five component An-Ab-Or-SiO_2-H_2O system in order to trace the theoretical course of crystallization of a granodiorite magma under 5000 bars water-vapor pressure. He plotted all experimental data available for the system at high water-vapor pressure in the anhydrous tetrahedron An-Ab-Or-SiO_2. In the component subsystems in which data at high pressure were lacking, analogy to the dry system was made in order to construct a reasonable "quaternary" diagram applicable to high water-vapor pressures.

Using Campbell's work as a model, a similar "quaternary" diagram was constructed for a water-vapor pressure of 2000 bars, (Fig. 28A). The quaternary system which forms the Or-Ab-SiO_2 face of the tetrahedron is the best known part of the system at low water-vapor pressures (Tuttle and Bowen, 1958). Yoder et al (1957) and Stewart (1957) have worked out the "binary" systems of the anorthite-orthoclase-quartz face of the diagram at high water-vapor pressure. All the binary and ternary systems have been studied at atmospheric pressure.

The surface ABCDEF splits the tetrahedron into two volumes in which, excluding the boundary surfaces, one solid phase coexists with a liquid and a water-rich fluid at a specified water-vapor pressure. Quartz can exist with liquid and gas above this surface. One feldspar can exist with liquid and gas in the volume below this surface. This feldspar is plagioclase on the An-side of the plane EFGH and is an alkali feldspar on the Or-Ab side. It should be pointed out, however, that the one-feldspar, solid region is continuous in the space between the line FG and the Or-Ab-SiO_2 face of the tetrahedron. Two feldspars plus liquid and vapor

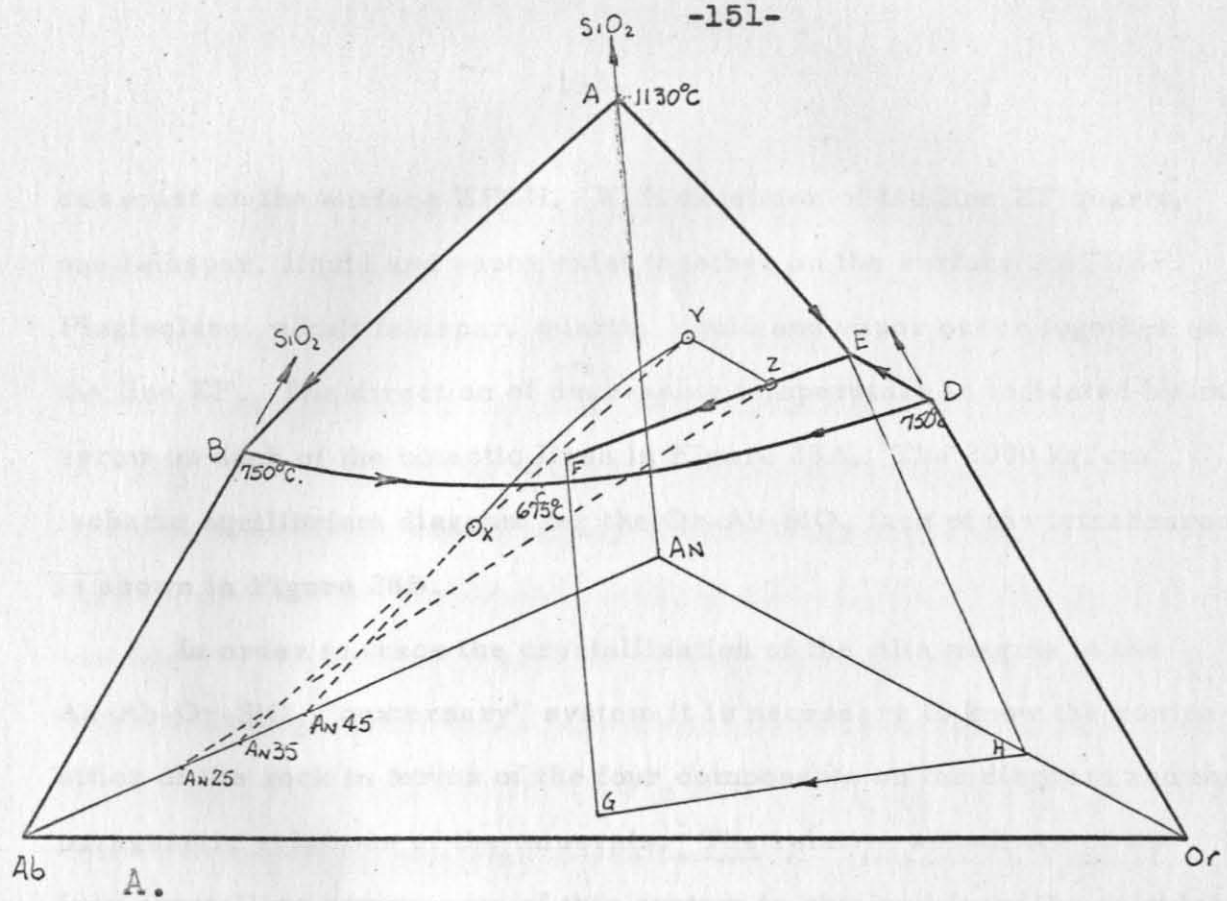
Figure 28. Phase diagrams in the system $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O.

A. Schematic phase diagram of the system $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O at moderate water-vapor pressure, plotted on the anhydrous tetrahedron An-Ab-Or-SiO_2.

B. The 2000 kg/cm^2 isobaric equilibrium diagram for the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O projected onto the anhydrous base of the $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O tetrahedron. After Figure 24 of Tuttle and Bowen (1958).

X-Y-Z-F (Fig. 28A) is the theoretical crystallization path of a granodiorite magma with the same proportions of Or, Ab, An and quartz as the calculated mineral composition of A-69-P. Quartz begins crystallizing at Y and K-feldspar begins at Z. Hypothetical tie lines X-X', Y-Y' and Z-Z' show composition of the plagioclase crystallizing from the magma at points X, Y and Z.

Points Gm and AP (Fig. 28B) are the average composition of the groundmass of the porphyritic granodiorite and the average composition of the aplite-pegmatite dikes, respectively cast in terms of Or, Ab and SiO_2. Point Gm' is the adjusted composition of the groundmass in which the oligoclase overgrowths on the plagioclase phenocrysts are included in the groundmass assemblage.


SiO2
A
1130°C
Y
Z
E
D
750°
SiO2
B
750°C.
F
675°
X
AN
AN 45
AN 35
AN 25
H
G
Ab
Or
A.

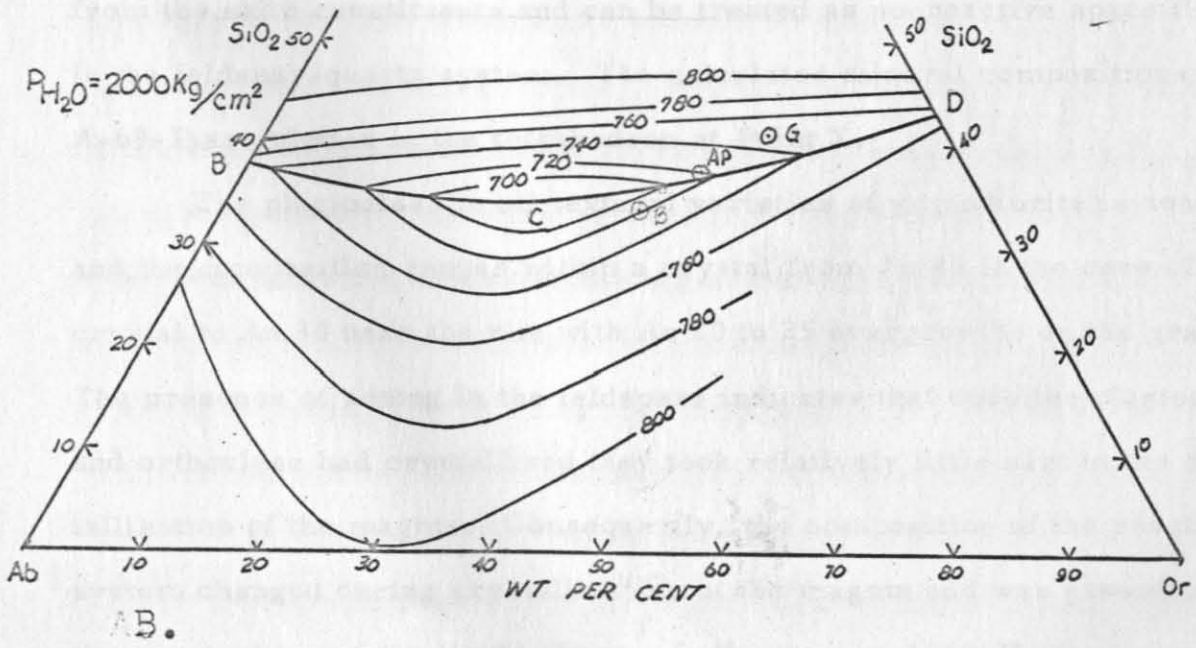

SiO2 50
50 SiO2
PH2O=2000Kg/cm2
800
780
760
740
720
700
D
G
AP
B
C
40
30
20
10
Ab
10
20
30
40
50
60
70
80
90
Or
WT PER CENT
AB.

Figure 28.

can exist on the surface EFGH. With exception of the line EF quartz, one feldspar, liquid and vapor exist together on the surface ABCDEF. Plagioclase, alkali feldspar, quartz, liquid and vapor occur together on the line EF. The direction of decreasing temperature is indicated by an arrow on each of the cotectic lines in Figure 28A. The 2000 kg/cm^2 isobaric equilibrium diagram for the Or-Ab-SiO_2 face of the tetrahedron is shown in Figure 28B.

In order to trace the crystallization of the Alta magma in the An-Ab-Or-SiO_2 "quaternary" system it is necessary to know the composition of the rock in terms of the four components on the diagram and the paragenetic relations of the minerals. The relative abundance of the four crystalline components of this system is obtained from the calculated mineral composition in Table 19. In this treatment, it is assumed that the biotite, hornblende, magnetite and sphene crystallized independently from the salic constituents and can be treated as nonreactive space fillers in the feldspar-quartz system. The calculated mineral compositions of A-69-P are plotted in the tetrahedron at Point X.

The plagioclase in all textural varieties of granodiorite is zoned and the composition ranges within a crystal from An 45 in the core of the crystal to An 30 near the rim with An 20 to 25 overgrowths on the grains. The presence of zoning in the feldspars indicates that once the plagioclase and orthoclase had crystallized they took relatively little part in the crystallization of the magma. Consequently, the composition of the reacting system changed during crystallization of the magma and was essentially the composition of the liquid phase. In the case of A-69-P, the composition of the liquid at the appearance of the first crystals was at the point

labeled X, well within the plagioclase field. Zoning in the plagioclase shows that as crystallization proceeded, the composition of the feldspar crystallizing from the melt became progressively more sodic. In the general case of the Alta magma, the composition of the liquid moved toward Y with falling temperature on a curved line approximately in the plane formed by the An-Ab edge of the tetrahedron and the point X. At the same time, the composition of the plagioclase changed from X' toward Y'. At Y, quartz began to crystallize along with plagioclase and the composition of the liquid moved on a curved path towards Z. At Z, K-feldspar began to crystallize along with quartz and plagioclase and the composition of the liquid moved toward F. If any liquid remains at point F, further cooling will crystallize only one feldspar. Hypothetical tie lines connecting plagioclase composition and liquid composition are shown for points X, Y and Z. Solid solution of orthoclase in plagioclase was ignored in plotting points X', Y' and Z'.

As was discussed earlier, the fine-grained groundmass probably represents a quenched residual liquid from the crystallization of the phenocryst assemblage of the porphyritic rocks. The porphyritic granodiorite contains approximately a 1:1 ratio of quartz to K-feldspar. The 2:1 ratio of quartz to K-feldspar in the phenocryst assemblage suggests that quartz began to crystallize earlier than K-feldspar. The fact that some orthoclase is in the phenocryst assemblage shows that the magma had reached the cotectic EF before crystallization of the groundmass.

The groundmass of the porphyritic granodiorite approximates a one-feldspar rock when considered separately from the phenocryst

assemblage. The composition of this feldspar is presumed to be principally orthoclase, but is most likely contains considerable albite in solid solution. It is possible, therefore, that the composition of the liquid in equilibrium with the phenocryst assemblage at the time of intrusion of the porphyritic granodiorite had almost reached the point F in Figure 28A. Point F moves farther from the Or-Ab-SiO_2 face of the "quaternary" system with decreasing pressure. Therefore it is entirely possible that change in crystallization from the two feldspars of the phenocryst assemblage to the one feldspar of the groundmass is related to a sudden lowering of water-vapor pressure.

As was suggested earlier, however, the oligoclase rims on the plagioclase phenocrysts may have crystallized with the groundmass and, therefore may represent the second feldspar phase that crystallized from the residual liquid. If this is the case, the composition of the magma remained on the cotectic EF even during emplacement and final crystallization of the porphyritic granodiorite.

Geologic relations indicate the aplite-pegmatite dikes were emplaced before the crystallization of the groundmass of the porphyritic granodiorites. It was suggested in an earlier section that these dikes may represent a liquid extract of a core differentiate of the Alta stock. These dikes are two-feldspar rocks and, therefore, crystallized on the cotectic EF.

No experimental work has been done on the geologically important cotectic EF, and the location of this boundary line in Figure 28A is only a guess. A desirable line of research, therefore, would be to analyze

products of fractional crystallization in igneous suites associated with granodiorites for which pressure information is available. The composition of the groundmass of the porphyritic granodiorite and the aplite-pegmatite dikes would presumably be closely related to the cotectic line at approximately 1700 kg/cm^2 water-vapor pressure.

Temperature. The groundmass of the porphyritic granodiorite was one of the last members of the Alta igneous suite to complete crystallization. The composition of this groundmass can be described quite well with the components of the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2. Because this system has been studied under pressures comparable to that at the depth of crystallization of the Alta stock, a minimum melting temperature can be estimated for the granodiorite. The 2000 kg/cm^2 isobaric equilibrium diagram for the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O projected on the anhydrous base of the tetrahedron is shown in Figure 28B (Tuttle Bowen, 1958, Fig. 24). The average composition of the groundmass cast in terms of albite, orthoclase and quartz is located at point Gm in Figure 28B. Point Gm is very close to the boundary curves at moderate water-vapor pressures, but considerably toward the orthoclase side of the minimum point. At 2000 kg/cm^2 water-vapor pressure, the nearest part of the cotectic curve to point Gm corresponds to a temperature of about 750°C. If the following assumptions are valid, the lowest temperature at which the groundmass of the porphyritic rocks was liquid is 750°C.

1. The water-vapor pressure was not enough different from 2000 kg/cm^2 to affect the estimate on the minimum melting temperature.

2. The modal composition of the groundmass represents the composition of a residual liquid formed by fractional crystallization of

a late-stage phase of the Alta magma.

3. The presence of other components (e.g., the mafic constituents) in the system has no appreciable effect on the estimated minimum melting temperature.

In the simplest case, the crystallization of anhydrous minerals from a hydrous silicate melt will result in the concentration of water in successive residual liquids. As crystallization of anhydrous minerals continues, the system will eventually become saturated with water and a vapor phase will form.

There is no direct evidence, however, that the Alta magma was saturated with water at any time during crystallization of the granodiorite. The vugs and pegmatitic crystals in the aplite dikes are evidence that a vapor phase was present during the crystallization of these rocks, but similar evidence is lacking in the granodiorites. Therefore, it is likely that even toward the end of the crystallization history, the granodiorite was not saturated with water and the water-vapor pressure at all times was somewhat less than the total pressure. A reasonably minimum value of the water-vapor pressure is that equivalent to the hydrostatic head for the minimum stratigraphic cover on the Alta stock. Assuming that water has an average density of one over the depth and temperature ranges involved, the minimum water-vapor pressure in the Alta stock at a depth of 20,500 feet would have been approximately 625 kg/cm^2. The true water-vapor pressure was probably between this value and the lithostatic pressure of 1700 kg/cm^2. The temperature and pressure relations in artificial systems containing a vapor phase at high pressure are not quantitatively applicable to natural systems in which the water-vapor

pressure and the total pressure are not the same. Qualitatively, however, the effect of decreased water-vapor pressure at constant total pressure will be to increase the liquidus temperature for a given composition. Consequently, 750°C is probably a true minimum temperature with respect to reasonable departures of water-vapor pressure from total pressure. The second assumption, that the modal composition of the groundmass can be translated into the chemical composition of a late-stage residual liquid in the crystallization history of the porphyritic granodiorite depends on the manner in which the modal analyses were made and the estimates of the compositions of the constituent minerals. In making a modal analysis of porphyritic rocks in which groundmass grains are counted separately from phenocrysts, decisions must be made not only as to mineral identification but also as to origin of the grains. In the case of overgrowths on the phenocrysts, it is difficult in some cases to distinguish material which crystallized with the phenocrysts and material which crystallized with the groundmass. Because the abundance of plagioclase phenocrysts, much more material would be expected to crystallize from the interstitial liquid onto the phenocrysts of plagioclase than onto the phenocrysts of either orthoclase or quartz. In order to estimate the effect of an error of this type on the estimate of the composition of the residual liquid, the abundance of the An 23 overgrowths on the plagioclase phenocrysts in thin section A-69-P was added to the abundance of plagioclase of the groundmass and an adjusted composition of the residual liquid was calculated (column B, Table 27). This adjusted composition, point

Gm' of Figure 28B, falls closer to the minimum than the unadjusted composition. Moreover, the K-feldspar of the groundmass may contain appreciable albite in solid solution. The composition of the residual liquid represented by the groundmass lies between points Gm' and Gm and probably fairly close to Gm'.

As suggested previously, the aplite-pegmatite dikes in the non-porphyritic granodiorite probably represent a liquid extract of a core differentiate of the Alta stock and may be a better sample of this residual liquid than the groundmass of the porphyritic granodiorite. The average modal composition of the aplite-pegmatic dikes in terms of the three components Or, Ab and SiO_2 of the system shown in Figure 28B is plotted at point AP. Point AP corresponds to a minimum-melting temperature of approximately 720°C at 1700 kg/cm^2 water-vapor pressure. As expressed before, the presence of vugs and pegmatitic crystals in these dikes suggests that the dikes crystallized in the presence of a vapor phase.

The third assumption, that the effect of additional components on the liquidus temperatures in the orthoclase-albite-SiO_2-H_2O system could be in error but at present there are no data to estimate quantitatively the effects of other constituents. The compositions of both the aplite-pegmatite dikes andthe groundmass are not in reality on the cotectic boundary BCD as shown in Figure 28B but are projected from the cotectic boundary EF in the anhydrous tetrahedron of the system as shown in Figure 28A. Using Figure 28B involves the assumption that for a given ratio of Or;Ab;SiO_2 the relations between temperature and water-vapor

pressure on the cotectic EF are similar to these relations on the cotectic DC.

The topology of the schematic diagram of Figure 28A shows that the temperature range of the cotectic EF is included in the temperature range on the cotectic CD and therefore the minimum-melting temperature read off of Figure 28B will be equal to or higher than the minimum-melting temperatures for corresponding compositions in the "quaternary" system.

In conclusion, the best estimate on the temperature at which the groundmass and the aplite-pegmatite dikes crystallized from analogy to experimental systems is about 720°C.

ORE DEPOSITS OF THE COTTONWOOD AREA

The following summary on the ore deposits of the Cottonwood area is taken from Calkins and Butler (1943, pp. 86-132).

Between 1867 and 1954, $40 million worth of lead, silver, gold, copper and zinc was produced from the Big Cottonwood and Little Cottonwood districts, which are known collectively as the Cottonwood mining area. Although 30 percent of the recorded production of the district was taken before 1880 from the now idle bonanza deposits, production is recorded from the area for every year up to 1954. The quantity of metals recovered from the ore is listed in Table 4, and the location of the major ore bodies is shown on Plates 1 and 2.

The ore deposits of the Cottonwood area can be divided into two classes: contact deposits and bed-replacement deposits. The contact deposits are mostly adjacent to the Alta stock or large offshoots from the

stock. The major gangue minerals of these deposits are magnetite, andradite garnet, diopside, vesuvianite, forsterite, muscovite and the rare mineral ludwigite, $(Mg, Fe^{2+})_4 Fe_2^{3+} B_2^{0}10)$. The principal ore minerals are chalcocite, bornite and chalcopyrite. The deposits are of low grade and the value of iron as a flux made the ores profitable to mine.

The bed-replacement deposits have accounted for nearly all the production from the area.

> Typically these deposits have been formed by the replacement of certain beds of limestone adjacent to crosscutting fissures; they are therefore more or less tabular in form, lie roughly parallel to the bedding, and pitch with the intersection of the replaced beds and the fissure - commonly to the northeast. (Calkins and Butler, 1943, p. 94).

Three beds are commercially important in the area: (1) a limestone member in the Ophir formation, (2) a dark "wormy" mottled dolomite in the Maxfield limestone, and (3) a fine-grained brittle dolomite 150 feet above the top of the Cambrian. In addition the breccia zones associated with the preintrusive thrust faults have been very productive.

Concerning the composition of the bed-replacement deposits, Calkins and Butler (1943, p. 95) say:

> In most of the deposits the earliest sulfide to be formed was pyrite, which was deposited in great abundance and was accompanied by varying amounts of iron carbonate and probably manganese carbonate. The deposition of pyrite was followed in most places by that of chalcopyrite, bornite, tetrahedrite, enargite, galena and sphalerite. Some deposits contain other minerals in various proportions, such as tungstenite, formed at a late stage, in the Old Emma deposit and bismuthinite in the Sells mine. The composition of the gangue varies considerably. Quartz, for example, is so scarce in some deposits that it can hardly be found without careful search, while in others it is abundant; in the Old Emma deposit is a large "chimney" consisting almost entirely of quartz.

> Iron and manganese carbonates occur in many deposits, probably in most, but are not very abundant. Barite is scarce in most of the deposits that have replaced limestone.

STRUCTURAL RELATION OF THE ORE DEPOSITS OF THE COTTONWOOD AREA TO THE ALTA STOCK

Most of the ore deposits in the area have an east to northeast trend. An important exception to this generalization is the Flagstaff-Emma ore zone underneath the high ridge north of Alta (Plate 2). Plate 41 of Calkins and Butler (1943) shows that this zone strikes N 60° W and is made up of bed-replacement bodies which are located on east-west en echelon fissures. At the higher levels in the zone, the replacement bodies from adjacent fissures coalesce to form one practically continuous bed of ore. The ore shoots plunge approximately 25° to the east and narrow with depth. The outline of the stopes, shown on Plate 2, indicates the east-west control on the location of ore shoots in the Flagstaff-Emma ore zone. The ore deposits are at higher elevations in the western or Flagstaff end of the zone and successive ore deposits toward the east begin and end at successively lower levels. The zone is 3200 feet long and has a vertical range of 1200 feet. The deepest ore body that was mined up to 1941 was the faulted continuation of the Old Emma ore body, which is in the eastern end of the zone and was mined down to an elevation of 8400 feet. The Old Emma ore shoot was the largest body of ore that was developed in the zone and is

> a replacement deposit in a breccia zone that probably represents a minor thrust fault ... The ore bodies in this area as in that to the northwest appears to decrease in size with increase in depth. ... The primary mineralization in the Old Emma deposit consisted mainly of the deposition of

> pyrite and galena in a gangue of quartz or of unreplaced limestone. There are lesser amounts of sphalerite, tetrahedrite, and tungstenite. In the lower workings the ore body contains a core composed mainly of quartz with only a small percentage of metallic minerals. (ibid. p. 129)

In the periphery of this quartz core the metallic minerals are more abundant and the gangue of the ore changes from quartz to unreplaced carbonate. A 100-foot thick dike of "granodiorite porphyry" in the lower, easternmost workings of the Flagstaff-Emma zone is shown on Plate 41 of Calkins and Butler (1943).

The ore deposits of the Flagstaff-Emma ore zone are separated from the Alta stock by the Silver Fork normal fault, which dips 45° to the west and has a minimum vertical displacement of 3000 feet (Calkins and Butler 1943, p. 61). Movement on the Silver Fork fault, as well as most of the other north-south faults took place after the deposition of the ore deposits. The western block which is the downthrown side of the fault contains the ore deposits. There has been no lateral displacement on the fault.

If the movement on the Silver Fork fault is reversed and the two blocks are restored to their original position, the Flagstaff-Emma zone of ore bodies are on the trend of the projection of the westward dikelike extension of the porphyritic granodiorite. In addition, the ore bodies in the western half of the zone overlie the 1300-foot lobe of granodiorite which breaks the otherwise rather smooth trace of the contact of the Alta stock in Grizzly gulch. No samples were collected in this critical area so it is not known in fact whether the porphyritic granodiorite extends as far as the contact in Grizzly gulch.

The relative structural position of the ore zone and the porphyritic

granodiorite suggests that although the N. 80° E. fissures are the local control on the location of individual bodies, the concentration of ore bodies in the N. 60° W. trend of the Flagstaff-Emma zone might possibly have been controlled by the emplacement of the dikelike extension of the porphyritic granodiorite.

The structural alignment of the Flagstaff-Emma ore zone and the porphyritic granodiorite leads to an additional interesting, although highly speculative conclusion. As was discussed previously, the emplacement of the porphyritic granodiorite took place late in the cooling history of the stock, and was accompanied by the release of part of the volatiles of the residual magma. Tentatively, it is suggested that the fluids which were released during the emplacement of this late phase of the magma were the same fluids which deposited the ore minerals in the Flagstaff-Emma zone.

The principal tunnels of the Michigan-Utah mine adjacent to the stock on the northwest (Plate 2), are drifts on the main N. 70° E. ore-bearing fissures in this mine. Restoration of the original structure on the Silver Fork fault also aligns the apparent N. 80° E. internal structure of the Flagstaff-Emma zone in the western block approximately with the abundantly mineralized fissure systems in the Michigan-Utah mine in the eastern block. The N. 80° E. ore fissures also coincide in direction with the strongly developed joint set in the northern part of the Alta stock. Because this strong jointing is not found in the porphyritic granodiorite, the jointing and possibly the ore-bearing fissures were

most likely formed before the solidification of the porphyritic granodiorite. This alignment suggests the possiblity that the Flagstaff-Emma ore deposits are the westward and upward continuation of the Michigan-Utah deposits. The Michigan-Utah deposits are 3000 feet structurally below the Flagstaff-Emma deposits and are at the same elevation as the outcrops of the porphyritic granodiorite within the stock. The failure of the Flagstaff-Emma ore bodies to persist in favorable strata to depths equivalent to the structural elevation of Michigan-Utah deposits indicates the Flagstaff-Emma ore deposits were not continuous with these deeper deposits and possibly had a more local source.

DISTRIBUTION OF SULFOPHILE ELEMENTS IN THE ALTA STOCK

The purpose of this trace-element investigation is to study the distribution of the ore-forming metals in the minerals of the least altered rocks of the Alta igneous suite. Co, Ni, Cu, Zn, Ag, As, Cd, In, Sn, and Pb were sought in the samples and all but As, Cd and In were found. Intramineral comparisons of samples which represent the various stages in a differentiation sequence are used in this study in an attempt to determine the behavior of these metals during the crystallization of the Alta stock. Sixteen samples were selected for mineral separation and trace-element analysis. The suite of samples includes representatives of every unaltered igneous phase of the Alta stock, with the exception of the border rock.

Sample Description

The mineral separates are identified by a letter-number system in which the number and the upper-case letters indicate the sample locality and rock type, respectively, and the lower-case letter identifies the mineral species. Thus, 69-P-k is the orthoclase mineral separate from porphyritic granodiorite sample A-69-P. The code used in this system is shown below.

b	biotite	m	magnetite
c	chlorite	p	plagioclase
h	hornblende	q	quartz
k	orthoclase	s	sphene
		t	total rock

The minerals which were separated from each of the rock samples are listed in Table 28 by sample locality (Plate 2). The geologic setting of each of the rocks used in the study is described below.

TABLE 28 ANALYZED MINERAL SEPARATES AND ROCK SAMPLES FROM THE ALTA STOCK

	Plagioclase	Orthoclase	Quartz	Hornblende	Biotite	Magnetite	Sphene	Total rock	
	p	k	q	h	b	m	s	t	other
A-58-S	x	x	x	x	x	x	x	x	
A-69-P	x	x		x	x	x	x	x	groundmass, apatite
A-95-N	x	x	x	x	x	x		x	
A-102-AP		x							
A-107-AP	x	x	x						
A-109-AP					x				
A-110-AP		x							
A-111-AP		x							
A-112-N	x	x		x	x	x	x	x	chlorite-biotite mixture
A-198-1-AP	x	x				x		x	
A-198-2-AP		x	x						
A-219-L	x	x						x	
A-232-AP		x						x	
A-299-ML		x		x	x	x	x		
A-322b-S		x		x	x	x	x	x	chlorite
A-353-AP							x		
A-365-H				x		x			

Sample A-299-ML collected 3000 feet west of Mt. Wolverine is from the best exposure of mafic layered granodiorite in the Alta stock. The specimen from which the minerals were separated came from the coarse-grained part of the block shown in Figure 16.

A-112-N and A-95-N are typical samples of the nonporphyritic granodiorite of the Alta stock. A-95-N was collected 500 feet south of the north contact of the stock on the north shore of Twin Lakes reservoir, 1100 feet west of the dam. A-112-N was collected in Albion Basin 550 feet north of the south contact of the stock. The granodiorite at A-112-N has sparse iron stain and crystals of mafic minerals on joint surfaces. Joint surfaces in other outcrops in this part of the stock have disseminated pyrite and rare copper stain. No pyrite or iron oxides other than magnetite were seen in thin sections from A-112-N. A-95-N is a very fresh rock and contains the least chlorite and sericite of any sample of granodiorite examined in thin section.

A-58-S is a subporphyritic granodiorite collected from a prominent glaciated knob 400 feet west of the lower terminus of the Mt. Millicent chair lift on the west side of the recreation area at Brighton. The sample locality is 1300 feet from the north contact of the porphyritic granodiorite and 1500 feet southeast of the contact of Alta granodiorite with sedimentary rocks. Thin sections of the rock used for mineral separation show a subporphyritic texture. The groundmass of the rock has an index of coarseness of 0.21 mm, which is much coarser grained than the groundmass of the average

porphyritic granodiorite. One thin section from another block collected at this locality had a nonporphyritic texture. Consequently, a complete gradation in texture probably exists within the outcrop of A-58-S. Minor iron stain occurs on joint surfaces, and relative to the other samples of granodiorite used in this study, A-58-S contains abundant chlorite.

A-69-P was collected in a quarry at the southeast end of Lake Mary dam within 200 feet of the contact with nonporphyritic granodiorite. The rock is strongly porphyritic and has wide-spaced joints with no iron staining. A-69-P contains the least chlorite and sericite of any porphyritic granodiorite examined in thin section.

A-322b-S is a sample of subporphyritic granodiorite which has prominent quartz crystals but very little interstitial groundmass. The rock was collected 1200 feet west of the north end of the Lake Mary dam. The rock has abundant chlorite, and epidote, and is one of the few rocks in which hematite was seen in thin section. The rock does not have much more sericite than A-69-P.

Samples A-198-AP and A-232-AP are from aplite-pegmatite dikes in the nonporphyritic granodiorite. Both sample locations are approximately 2000 feet from outcrops of porphyritic granodiorite. Sample A-232-AP was collected from the center of a 7-inch thick dike on the north shore of Twin Lakes reservoir about 150 feet southwest of sample locality A-95-N. A-198-AP was collected from a three-inch dike located 500 feet south of the top of Mt. Tuscarora. Sample A-198-AP was analyzed in two parts; A-198-1-AP is the

aplitic margin of the dike and A-198-2-AP is the pegmatitic textured core of the dike. A-232-AP has a micrographic texture. No pyrite was seen in either of these dikes. Accessory biotite, hematite and chlorite are found in both dikes. The orthoclase of A-232-AP is strongly perthitic, but the orthoclase of A-198-AP has only a weak perthitic texture.

Sample A-107-AP is from an aplite dike in the wall or a large inclusion of wall rock in the border zone at the south contact of the stock. The sample was collected on the dump of a small prospect 1700 feet S. 55° W. of the top of Mt. Wolverine at an elevation of 9960 feet. The dike has an aplitic texture in the outer part of the dike and a coarse-grained graphic texture in its center (Fig. 26). The sample used for the trace-element work is a 2-inch thick slab cut perpendicular to the walls of the dike.

Sample A-219-L is a leucocratic quartz monzonite dike which intrudes subporphyritic granodiorite in the central part of the body of porphyritic granodiorite. The sample was collected 850 feet N. 50° W. from the north end of Lake Mary dam.

The four samples A-102-AP, A-109-AP, A-110-AP and A-111-AP are from the Albion Basin pegmatite. A-102-AP is from a 10-inch thick layer of pegmatite located four feet below the top of the 20 foot-thick pod. A-109-AP and A-110-AP are from a three-foot layer of pegmatite, 10 feet below A-102-AP. A-111-AP is a sample of the micrographic textured rock at the base of the pod.

Sample Collection and Preparation

Early in the study, thin sections were cut from hand specimens taken from the least weathered and least altered rocks seen in the Alta stock. Samples whose thin sections contained the least chlorite, sericite, clay minerals and epidote were selected for geochemical study. Enough material was collected from the sample locality to make an aggregate of at least 2 kg. Weathered rock and stained joint surfaces were avoided. Undesirable material was trimmed from the sample at the outcrop location and the remainder stored in cardboard cartons and paper bags.

The samples were crushed in a diamond mortar two inches in diameter, and screened with silk bolting cloth. The samples were first broken up in fragments which could fit in the barrel of the diamond mortar. Between 150 and 1000 grams of these coarse fragments were then crushed until all the material passed through 100-mesh bolting cloth. The crushed rock was quartered repeatedly and 5 to 40 grams were set aside as a sample of the whole rock. Grains which passed 100-mesh and were retained on 200-mesh bolting cloth were used for the mineral separation procedure. This fraction contains relatively few composite grains of the major minerals in the nonporphyritic rocks.

Both heavy liquids and the Frantz magnetic separator were used to separate the minerals from the 100-mesh to 200-mesh size fraction of the crushed rock. Initial separations were made in s-tetrabromoethane (TBE)-acetone mixtures in one-liter separatory funnels using 50 to 100 grams of material at a time. The heavy

liquids were removed from the separates by filtering and repeated washing with acetone.

Orthoclase, plagioclase and quartz concentrates were obtained by repeated adjustments in the density of the TBE-acetone mixture. The density of the liquid was controlled by comparison with a set of mineral fragments whose specific gravity had been determined with a pycnometer. Because of their fine grain size the groundmass minerals of the porphyritic rocks form composite grains of quartz and orthoclase in the 100-mesh to 200-mesh size fraction used in the mineral separation procedure. These aggregate grains have an average density of 2.62 and could therefore, be separated from single grains of quartz and orthoclase of the phenocryst assemblage. The groundmass separate was passed through the magnetic separator and the nonmagnetic fraction was retained for trace-element analysis.

It was found that a liquid with a density of 2.8 produced a fairly clean separation of the orthoclase, quartz and plagioclase from the mafic minerals. Although tetrabromoethane (sp.g. 2.95) and diiodomethane (sp.g. 3.3) were used in the separation procedure, the Frantz magnetic separator is the most useful tool in making separations in the mineral group with density greater than 2.8.

Purity of the mineral concentrate was determined by making grain counts in oils with appropriate indices of refraction. Purity of quartz and plagioclase concentrates was determined by washing a few mg of the mineral separate in HF and counting the number of

TABLE 29. PURITY OF MINERAL SEPARATES

	Purity %	Remarks
Orthoclase		
198-2-AP-k_1-1	96	2% quartz, 2% albite, 0.05% biotite
232-AP-k	97	
95-N-k	94	
219-L-k	90	9% quartz
69-P-k	94	
58b-S-k	97	
198-2-AP-k_2	99	sp. g. < 2.57
198-1-AP-k	96	3% quartz, 1% albite
112-N-k	95	
111-AP-k	91	quartz composite grains
107-AP-k	97	composite grains
102-AP-k	94	quartz composite grains
109-AP-k	99	perthite
110-AP-k	99.5	0.5% biotite, perthite
299K-ML-k	99	
322b-S-k	96	plagioclase, quartz
Plagioclase		
58-B-S-p_1-1	95	5% quartz, sp. g. 2.67 to 2.65$^+$
58-S-p_1-2	90	sp. g. 2.67 to 2.65$^+$
95-N-p_1	95	sp. g. 2.67 to 2.65$^+$
95-N-p_2	75	sp. g. < sp. g. quartz
58-S-p_2	98	sp. g. 2.645 to 2.63
69-P-p_1	96	sp. g. 2.67 to 2.66
69-P-p_2	90	sp. g. 2.66 to 2.65$^+$
198-1-AP-p	ca. 85	8% orthoclase, 5% quartz, sp. g. < 2.648
219-L-p	ca. 70	ca. 30% quartz, no orthoclase, sp. g. < 2.635
112-N-p	99	sp. g. 2.67 - 2.65$^+$
107-AP-p	78	10% quartz, 12% composite, sp. g. 2.64 to 2.635

Table 29. (Continued)

	Purity %	Remarks
Quartz		
95-N-q	85	
58-S-q	95	
198-2-AP-q	99	
112-N-q	90	10% plagioclase
107-AP-q	99	
Biotite		
112-N-b	95	2.8% chlorite, 1.8% hornblende, 0.5% sphene
58-S-b	97	2% chlorite, 1% hornblende
299-ML-b	93	6% chlorite, 1% hornblende
95-N-b	95	3% chlorite, 1% plagioclase, 1% hornblende
69-P-b	96	4% chlorite + composite grains
322b-S-b	96	4% chlorite, sphene
109-AP-b	--	
69-P-b	95	5% chlorite
Hornblende		
112-N-h	98	1% biotite
69-P-h	100	
299-ML-h	95	3% biotite, 2% fledspar and quartz composite
95-N-h	99	
58-S-h	98	plagioclase, apatite, zircon < 1% biotite
322b-S-h	93	5% biotite, 1% apatite, 1% allanite, 1/4% sphene
365-H-h_1		
365-H-h_2		

TABLE 29. (Continued)

	Purity %	Remarks
Sphene		
112-N-s_1	98	Sp. g. > 3.3
299-ML-s	100	
58-S-s	97	3% apatite
69-P-s_1	99+	
69-P-s_2	100	less magnetic than s_1
322b-S-s	99	1% apatite
353c-AP-s	--	
365b-H-s	--	
112-N-s_2	--	sp. g. ≤ 3.3
Magnetite		
112-N-m	)0	10% composite with hornblende and felsic minerals
299-ML-m	)6	4% composite with feldspar
586-S-m	)1.5	1-1/2 % hornblende, 1-1/2 % biotite, 5% feldspar, 0.5% chlorite
59-P-m	--	
322b-S-m	)7	Biotite, hornblende, apatite
198-AP-m	--	
95-N-m	--	

unetched grains to determine the percentage of quartz in the sample. The purity of the mineral separates and the composition of the impurities is shown in Table 29.

To check for possible contamination of the samples with sulfophile elements in the sample preparation procedures, some clean quartz and microcline were crushed in the diamond mortar, washed for several hours in heavy liquids and vibrated on the copper trough of the magnetic separator. These test samples were then analyzed along with fractions of the same material which had been crushed only in an agate mortar. The copper trough of the magnetic separator contributed detectable amounts of copper to the test samples. After the trough was plated with rhodium metal no copper or any other sulfophile element was added to the sample in detectable amounts in the general mineral separation procedure.

Analytical method

The spectrographic procedures and equipment used to analyze the mineral concentrates and rock samples from the Alta stock are summarized below.

Spectrograph: A Jarrel-Ash, 21-foot, Wadsworth-mounted, grating-type instrument with a dispersion of 5.2 Å per mm in the first order. Nonfluorescent lenses were used to increase sensitivity in the ultraviolet region.

Electrodes: The anodes were shaped from 1/4-inch high-purity graphite rods. The cathodes were two-inch long pieces of

1/8-inch diameter graphite rod pointed on one end.

Photographic plates: 4 x 10 inch, Eastman Kodak, emulsion number 103-0, sensitized for the ultraviolet light. Plates were developed four minutes at 20°C in DK-50 developer.

Wavelength range: 2300-3550 Å in the first order.

Excitation: Sample was used as the anode. A D. C. arc was adjusted to give 19.0 amperes with the electrodes short circuited. The analytical gap was 4 mm. The central two mm were focussed on a diaphragm, and this image in turn focussed on the slit with a vertical cylindrical lens. Total energy method was used with no internal standard.

Exposure: The slit width was 25 microns. Two-step quartz filter and 9° to 12° rotating sector were used to reduce the amount of light transmitted. Exposure of 50 seconds was used for the more volatile elements, lead, zinc and silver, and a complete burn was used for the less volatile elements, copper, cobalt, nickel and tin.

Plate calibration: Selected iron lines after the method of Dieke and Crosswhite (1943).

Electrode charge: 25 mg of sample plus matrix. Plagioclase, orthoclase, quartz and rock samples are mixed in the proportions of 40 sample, 10 carbon and 3 Na_2CO_3. Biotite, hornblende and magnetite are mixed in the following proportions: 4 sample, 3 quartz, 2 carbon and 1 NaCl. Sphene is diluted in the following proportions: 2 sample , 5 quartz, 2 carbon and 1 NaCl.

Standards: Spectrographically pure oxides added to a pure

lead-free feldspar base diluted in the proportions described above.

Analytical lines: See Table 30.

Sensitivities: See Table 30.

The method used in this study differs from standard emission spectrographic technique in the high alkali content of the matrix in the burn and the incomplete volatilization of the sample in the determination of Ag, Pb and Zn.

The sensitized plates were obtained in order to make use of the very sensitive zinc line at 2138 Å. Although very low concentrations of zinc could be recorded at this wavelength the emulsion of this film was not responsive to changes in concentration of zinc in the burn. Consequently the less sensitive zinc line at 3345 Å had to be used.

Up to fourteen samples can be burned in duplicate on each plate. One or more standards are burned on each plate. Because there is more chance for error in comparing analyses of samples from different plates, all the samples of each mineral species were analyzed together on the same plate.

The reproducibility of the emission spectrographic method is evaluated in two ways. In the first method the difference between duplicate analyses is used to estimate the standard deviation for each element (Dixon and Massey, 1957, p. 273). The difference between duplicate analyses is expressed as a percentage of the mean value for the duplicates. These relative differences are averaged for each element and multiplied by 0.886 to give the relative standard deviation. The standard deviation computed by this method is

TABLE 30. WAVELENGTH AND SENSITIVITY OF ANALYTICAL LINES

Element	Wavelength	Sensitivity in ppm	
		felsic minerals	mafic minerals
Ag	3280.7	0.07	0.25
Co	3453.2	1	20
Cu	3274.0	0.5	3
Ni	3414.8	0.5	5
Pb	2833.1	3	3
Sn	2840.0	10	15
Zn	3345.0	35	40[a]

(a) 200 ppm for sphene, hornblende and magnetite.

TABLE 31. REPRODUCIBILITY

Element	%	
	1	2
Ag	17	
Co	16	
Cu	12	30
Ni	21	
Pb	10	7.5
Sn	12	
Zn	12	

Column

1. Relative standard deviation of the mean from duplicate burns of all samples.
2. Relative standard deviation of the mean from replicate analyses of 69-P-k.

listed in column 1 of Table 31. This standard deviation should be valid at all concentrations but inspection of the data indicates that it is higher near the detection limit.

The relative standard deviation for copper and lead of the orthoclase sample 69-P-k was also computed from 14 burns on 6 plates. The standard deviation computed by this method (col. 2, Table 31), is higher for copper and lower for lead than the relative standard deviation computed by the other method. This is probably due to the relatively lower abundance of copper and higher abundance of lead in the orthoclase than in the other minerals.

Data

Data on the abundance of trace elements in rocks and minerals of the Alta stock are given in Tables 32 through 39. The concentrations are given generally in parts per million by weight (ppm), and are reported to two significant figures in most analyses. The abundance of iron in sphene is reported as percent Fe_2O_3. A dash (-) indicates an element was not detected. Some samples were not analyzed for certain elements and are indicated by an asterisk (*). Each number in the tables is the arithmetic average of duplicate analyses. For a few samples no meaningful average could be obtained owing to disagreement of the duplicate analyses or other reasons; these are indicated by a query (?).

TABLE 32 ANALYSES OF HORNBLENDE

ppm

Sample		Cu	Ag	Co	Ni	Zn
58-S-h	1	3.2	1.0	31	21	
	2	*	*	*	*	200?
	3	10.5	1.1	43	34	*
69-P-h	1	5.5	0.9	36	28	*
	2	*	*	*	*	225?
	3	5.9	1.2	39	29	*
95-N-h	1	7.6	1.0	36	21	*
	2	*	*	*	*	270?
	3	14	0.9	35	24	*
112-N-h	1	12	1.2	34	16	*
	2	*	*	*	*	300?
299-N-h	1	2.8	*	26	24	*
	2	3.0	0.85	32	28	*
	3	*	*	*	*	300?
	4	3.3	0.8	49	36	*
322b-S-h	1	59	1.05	31	21	*
	2	*	*	*	*	100
	3	89	1.35	33	30	*
365-H-h	1	57	0.95	30	29	*
	2	*	*	*	*	160
	3	*	*	*	*	80
	4	50	2.2	24	19	*

Pb and Sn: * or -

TABLE 33 ANALYSES OF BIOTITE

ppm

Sample		Cu	Pb	Ag	Zn	Co	Ni
112-N-b	1	43	-	0.5	550	*	*
	2	53	-	0.7	500	*	*
	3	64	-	*	505	41	34
	4	*	6.6	*	625	*	*
58-S-b	1	13	-	0.6	390?	*	*
	2	18		*	440	48	37
	3	*	4.0	*	370	*	*
95-N-b	1	14	-	0.4	390	*	*
	2	24	-	*	425	38	38
	3	25	*	0.85?	*	53	58
	4	*	3.5	*	485	*	*
69-P-b	1	24	-	*	510	36	39
	2	23	-	0.8?	*	48	51
	3	*	2.5	*	540	*	*
	4	30	-	1.2?	*	72	56
	5	41	-	1.0	*	61	57
109-AP-b	1	32	-	*	350	22	18
	2	27?	-	0.25	*	41?	?
	3	*	5.1	*	174	*	*
299-ML-b	1	34	-	0.65	375	*	*
	2	24	-	*	400	45	41
	3	33	-	0.9	*	63	43
	4	26	-	1.15	*	72	50
	5	*	4.6?	*	485	*	*
322-S-b	1	215	-	*	440	38	35?
	2	250	-	0.9	*	54	48
	3	*	2.3	*	410	*	*

Sn: - or * all

TABLE 34. ANALYSES OF PLAGIOCLASE

Sample		Cu	Pb	Zn	Ag
		ppm			
58-S-p_1	1	3.5	15	30	--
	2	2.0	12.5	--	--
58-S-p_2		1.2	11.5	--	--
69-P-p_1		1.3	10	--	--
69-P-p_2		1.3	11.5	--	--
95-N-p_1	1	5.0	15.0	--	--
	2	1.6	14	--	--
	3	4.4	*	*	*
	4	4.5	*	*	*
95-N-p_2		1.1	11.5	--	--
112-N-p	1	4.0	13	--	--
	2	3.9	13	--	
198-1-AP-p		42	13	--	--
219-L-p		6.5	6.5	--	--

Ag, Co, Ni, and Sn: * or -

TABLE 35. ANALYSES OF ORTHOCLASE

Sample		Cu	ppm Pb	Ag
58-S-k	1	1.7	30	--
	2	0.7	29	--
	3	4.0	30	--
69-P-k	1	3.5	44	--
	2	2.2	42.5	--
	3	1.9	45.5	--
	4	1.6	48	--
	5	1.5	43	--
	6	1.2	48	--
	7	*	38	--
95-N-k	1	4.5	38	--
	2	3.6	37	--
	3	1.7	37	--
	4	3.0	42	--
102-AP-k	1	3.5	86	--
	2	3.3	63	--
	3	2.7	58	--
107-AP-k	1	*	93	--
	2	0.7	65	--
109-AP-k	1	2.0	85	--
	2	2.2	65	--
110-AP-k	1	2.0	80?	--
	2	1.3	76	--
111-AP-k	1	4.5	115	--
	2	2.9	61	--
112-N-k	1	5.5	41	--
	2	2.5	29.5	--
	3	1.3	26	--
198-1-AP-k	1	10.5	37	*
	2	7.4	35	0.07
	3	4.3	34	*
198-2-AP-k	1	8	44	--
	2	9.5	33	--
	3	7.2	40	0.1
	4	7.2	48	--
	5	2.6	30	--
219-L-k	1	5.0	32	--
	2	2.9	26.5	--
	3	1.6	28	--
232-AP-k	1	7.0	44	--
	2	7.5	38	0.07
	3	3.7	35	--
299-ML-k		0.8	26	--
322b-S-k	1	7.6	21	--
	2	*	22	--

Zn, Co, Ni and Sn: - or *

TABLE 36. ANALYSES OF MAGNETITE

Sample		Cu (ppm)	Ag (ppm)	Co (ppm)	Ni (ppm)
58-S-m	1	94	*	50	52
	2	105	1.8	64	59
69-P-m	1	75	*	58	58
	2	73	1.7	62	58
95-N-m		62	1.8	170	138
112-N-m	1	270	2.1	52	45
	2	200	1.9	60	50
	3	200	*	72	62
	4	185	1.2	33?	27?
198-AP-m	1	122	2.3	135	95
299-ML-m	1	45	*	78	79
	2	48	1.8	78	81
322b-S-m	1	180	*	35	48
	2	192	1.2	40	54

Sn, Pb and Zn: *

TABLE 37. ANALYSES OF SPHENE

Sample		Cu (ppm)	Ni (ppm)	Sn (ppm)	Fe_2O_3
58-N-s	1	63	--	73	2.2
	2	57	*	115	2.1
69-P-s_1	1	49	--	105	2.5
	2	63	*	125	2.6
69-P-s_2	1	58	6.5	70	2.0
	2	69	*	89	2.1
112-N-s_1	1	58	18	105	2.7
	2	57	*	145	2.5
112-N-s_2	1	42	--	77	2.0
	2	63	*	105	2.2
299-ML-s	1	54	--	70	2.5
	2	81	*	69	2.3
322b-S-s	1	70	--	105	2.4
	2	76	*	140	2.5
253-AP-s	1	62	4.9	470	2.5
	2	50	*	550	2.8
	3	57	*	770	3.8?
365-H-s	1	58	*	76	2.1
	2	68	*	125	2.7

Co, Pb, Ag and Zn: - or *

TABLE 38. ANALYSES OF TOTAL ROCK

Sample		ppm Cu	Pb	Ag	Zn	Remarks
58-S-t	1	8.0	4.0	0.04	40?	
	2	*	11.5	*	53	
69-P-t	1	9.0	10	0.04	76	
	2	9.5	11.5	*	75	
	3	*	14	*	79	
95-N-t	1	7.5	7.0	0.05	49	
	2	*	14	--	65	
112-N-t	1	27	10	0.04	68	
	2	*	13	*	68	
198-1-AP-t	1	10.5	37		--	
	2	20	13.5	0.06	--	
	3	21	15.5	*	--	
	4	*	19	*	--	
219-L-t	1	13	10.5	0.04	--	
	2	*	10	*	30	
	3	11.5	10	0.03	--	Mag fraction removed
232-AP-t	1	30	20	0.04	--	
	2	*	17	*	--	
	3	25	21	0.13	--	Mag fraction removed
	4	26.5	20	0.15	--	
322b-S-t	1	135	*	*	*	
	2	*	13	*	42	

Co, Ni and Sn: *

TABLE 38a. MISCELLANEOUS ANALYSES

Quartz		ppm Cu	Pb	Zn	Ag
107-AP-q	1	6.5	--	--	--
	2	1.6	5	--	--
112-N-q	1	7.5	3	--	--
	2	4.7	7	--	--
95-N-q	1	1.3	--	--	--
58-S-q		1.4	7	--	--
198-2-AP-q		7.7	--	--	--

Co, Ni and Sn: *

Other		Copper	Lead	Zinc	Silver	Cobalt	Nickel
69-P-gmass		Groundmass, density 2.62, of A-69					
	1	4.0	22	--	--	*	*
	2	2.6	30	--	--	*	*
112-N-b, c		Approx. 40% chlorite, 60% biotite					
	1	135	13?	740	0.75	*	*
	2	150	*	680	*	70	45
	3	*	14	875	*	*	*
322b-S-c		95% chlorite					
		320	*	*	1.6	83	95
69-P-apatite		*	5	--	*	*	*

Sn: *

Discussion

The samples used in this study represent various stages in the differentiation sequence deduced for the Alta stock. The sequence of rock types and the relation of the analyzed samples to this sequence are shown in Figure 29. If the minerals from these rock samples represent crystal growth in successive residual liquids, comparison of the trace-element content between samples of the same mineral species should indicate if the ore-forming trace elements were fractionated in the differentiating magma.

The number of variables affecting trace-element substitution is minimized by making only intramineral comparisons and restricting the study to the relatively unaltered rocks of the Alta igneous suite. In order to use the trace-element data of the minerals to indicate the trend in the trace-element abundances of the successive fractions of the magmas from which the minerals crystallized, however, it must be assumed that changes in temperature, pressure and bulk composition of the magma from which all the samples of a mineral species grew had little effect on the trace-element uptake of that mineral species. An additional assumption is that small changes in the bulk composition of the minerals did not appreciably affect the distribution of sulfophile elements between mineral and magma. If these assumptions are valid, then variations in trace-element content in the mineral sequences will reflect variations in the trace-element content of successive fractions of the magma. The validity of the assumptions is discussed below for

Oldest		Samples
1.	Border rock	None
	Mafic layered granodiorite	A-299-ML
2.	Nonporphyritic granodiorite	A-95, A-112-N
3.	Phenocryst assemblage of subporphyritic and porphyritic granodiorite	A-58-S, A-69-P, A-322b-S
	Hornblendite veinlets	A-365-H
4.	Aplite-pegmatite dikes	A-107, A-198-AP, A-232-AP, A-353-AP
	Groundmass of subporphyritic and porphyritic granodiorite	A-69-P
	Albion Basin pegmatite	A-102-AP, A-109-AP A-110-AP, A-111-AP
5(?)	Leucocratic quartz monzonite dikes	A-219-L
Youngest		

Figure 29. Differentiation sequence in the Alta igneous suite. The samples used in the trace-element study are indicated in the column at the right.

each mineral.

In Figures 30 through 39 the trace-element data are plotted as a function of position of the rocks and minerals in the differentiation sequence. The vertical line above each mineral-separate number shows the range of values recorded. Individual analyses are shown by a dash (-). The vertical lines between sample numbers separate the samples into the groups shown in Figure 29. The earliest rocks and minerals to crystallize in the stock are plotted on the left of the diagrams and successively younger groups of rocks and minerals are plotted toward the right. Within each group, no relative age is implied by the order in which the samples are listed.

Hornblende. Analyses of hornblende samples are found in Table 32 and the data are plotted in Figures 30 and 31, according to relative position in the differentiation sequence. Only three groups of hornblendes are distinguished in the Alta stock. Hornblende from the three textural types of granodiorite crystallized early and probably from a common magma. Therefore samples 112-N-h, 95-N-h, 69-P-h, 58-S-h, 322b-S-h are treated as a group in Figures 30 and 31. Because the mafic layered granodiorite is a cumulate of early-formed crystals, the sample 299-ML-h may represent hornblende which crystallized much earlier than the hornblende in the main body of granodiorite.

The youngest hornblende, 365-H-h, crystallized from a fluid of quite different composition than that in which the hornblende of the granodiorite originated and, therefore, only tentative conclusions can be made concerning the relation of the metal content of the

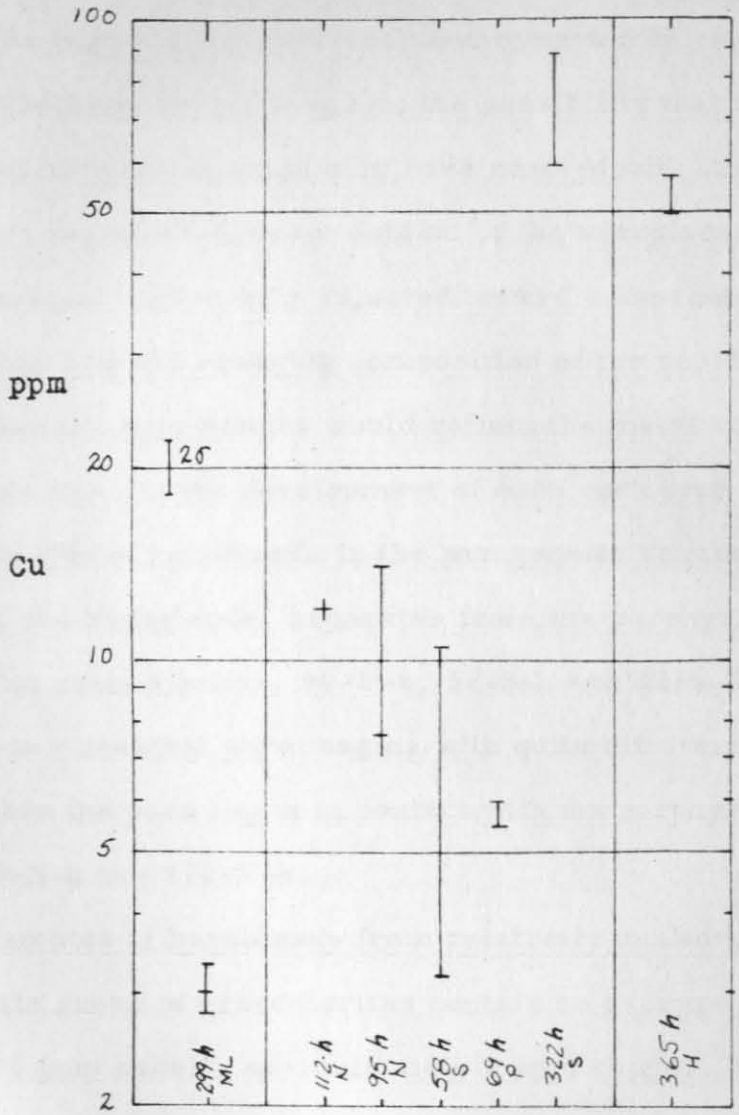


Figure 30. Copper in hornblende. Two times the relative standard deviation of the mean is shown graphically (2σ). The dashes (-) indicate individual analyses and the length of the vertical lines connecting the analyses is the range of the data.

fluid which formed 365-H-h to the metal content of the magma which formed the hornblendes in the granodiorites.

The high abundance of included minerals in replacement relation to the hornblende, suggests the possibility that all parts of the typical hornblende grain may have reacted with the residual liquid. Moreover, the trace-element content of the unreplaced hornblende may have been continuously adjusted toward a concentration in equilibrium with the changing composition of the residual liquid. In this case the hornblendes would reflect the metal content of a pore liquid later in the development of each rock type than indicated by the position of hornblende in the paragenetic sequence. If this is the case, the hornblende separates from the porphyritic and subporphyritic granodiorites, 69-P-h, 58-S-h and 322b-S-h, may have adjusted to a residual pore magma with quite different trace-metal content than the pore liquid in contact with nonporphyritic granodiorites, 95-N-h and 112-N-h.

Samples of hornblende from relatively unaltered samples of the main group of granodiorites contain an average of 1.0 ppm silver, 35 ppm cobalt, approximately 8 ppm copper, < 3 ppm lead, 25 ppm nickel, < 15 ppm tin and ≤300 ppm zinc. Cobalt and nickel in hornblende are slightly more abundant in the mafic layered granodiorite and slightly less abundant in the hornblendite veinlet than in the main group of granodiorites. Copper in hornblende is highly variable but is probably significantly lower in the mafic layered granodiorite and higher in the hornblendite veinlet. The hornblende from the relatively altered subporphyritic granodiorite, A-322b-S,

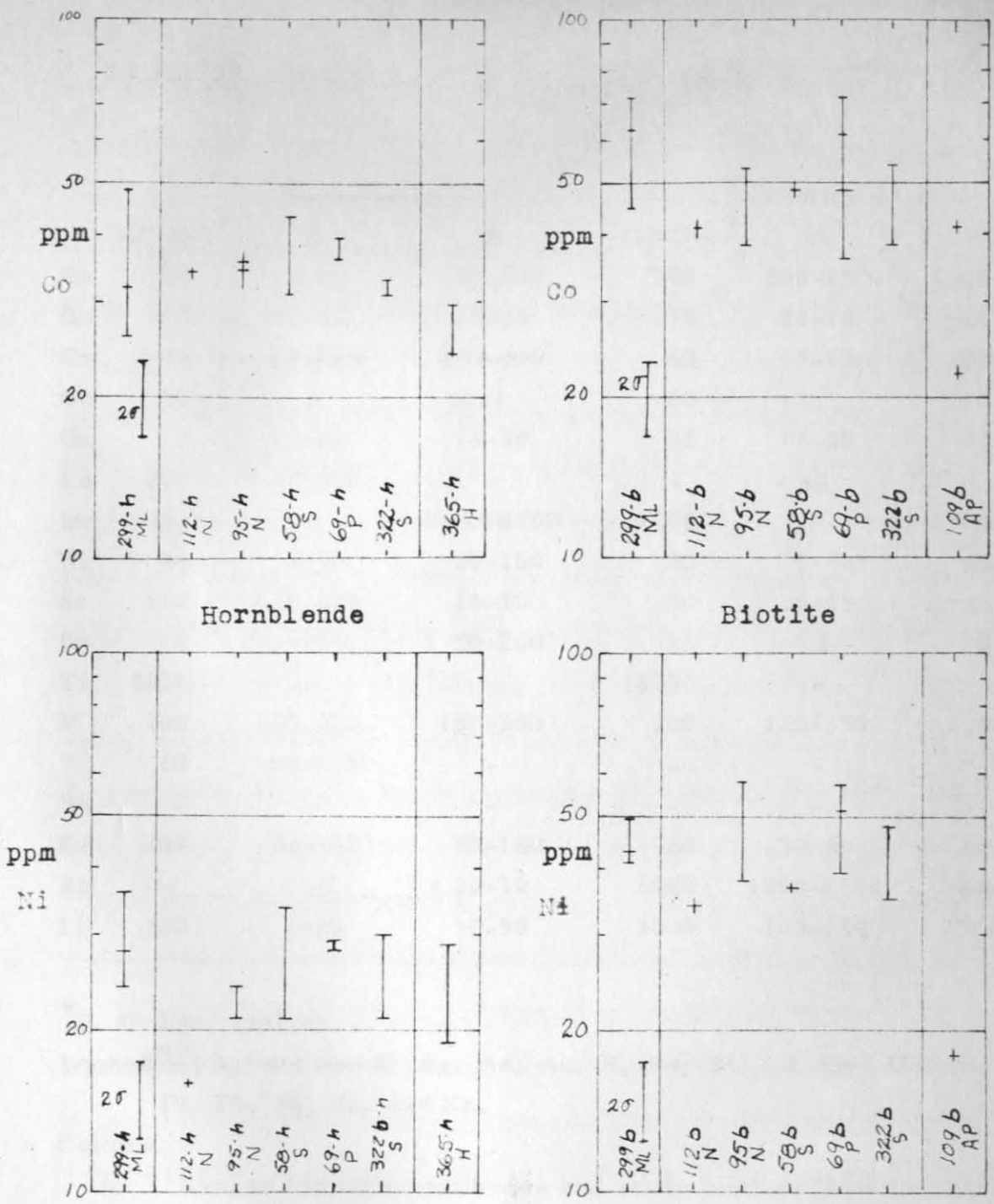


Figure 31. Cobalt and nickel in biotite and hornblende. See Figure 30 for explanation.

TABLE 39. TRACE ELEMENTS IN HORNBLENDE AND BIOTITE FROM A-112-N

ppm

	Hornblende			Biotite		
	112-N-h*	A	B	112-N-b*	A	B
Ba	55	10-80	20-100	7300	500-2500	1000-3000
Co	70	12-45	20-30	70	20-70	20-35
Cr	40	15-125	200-400	60	10-125	100-500
Cu	20	-	≤ 10	60		10-20
Ga	2	15-20	15-30	25	15-30	20-50
La	200	40-200	-	-	< 40	-
Mn	5000	-	2400-4300	2000	-	1500-3000
Ni	40	5-55	80-100	50	5-90	45-150
Sc	140	100-150	15-30	20	5-35	≤ 10
Sr	8	< 2-15	50-200	13	< 2	70-100
Ti	5000	-	-	10000	-	-
V	200	125-265	100-300	200	120-350	200-400
Y	60	65-300	-	-	-	-
Yb	6	-	-	-	-	-
Zr	200	50-180	50-150	60	30-50	< 10-20
Rb	-	< 10	< 20-30	6000	1000-1500	800-2000
Li	100	5-20	10-30	3000	100-250	250-800

*E. Godijn, analyst.

Looked for but not found: Ag, As, Au, B, Be, Bi, Cd, Ge, Mo, Nb, Pt, Pb, Sb, Sn, and Zn.

Column

A Ranges for six hornblendes and seven biotites from tonalites and granodiorites of the southern California batholith (Sen et al., 1959).

B Ranges for four hornblendes and five biotites from tonalites and granodiorites from Caledonian plutonic rocks of western Scotland (Nockolds and Mitchell, 1948).

contains an anomalously high copper content. This hornblende concentrate, however, does not contain an abnormally high percentage of impurities.

The hornblende and biotite of A-112-N were also analyzed by E. Godijn using a more general technique in which 17 trace elements were detected in the samples. These two analyses are shown in Table 39 along with some data on the range in trace-element composition of hornblende and biotite from the southern California batholith (Sen et al., 1959) and from Caledonian igneous rocks of western Scotland (Nockolds and Mitchell, 1948). The hornblende from A-112-N contains more Co, Cu, La, and Li than the suite of hornblendes listed for comparison. The biotite of A-112-N contains more Ba, Co, Cu, Zr, Rb and Li than the range of trace-element values for the suite of biotites listed in the table.

Rose (1958) analyzed biotite and hornblende from granodiorite stocks in the Hanover-Santa Rita mining area, New Mexico. Hornblende from the Hanover-Fierro stock contains 20 ppm Cu, 25 ppm Co and 3000 ppm Mn. Biotite from both the Santa Rita and the Hanover-Fierro stocks contains 40 ppm Co, 25 ppm Ni and 175 ppm Zn. The biotite from the Hanover-Fierro stock, which is associated primarily with zinc deposits, contains 120 ppm Cu. The biotite from the Santa Rita stock in which the Santa Rita porphyry copper deposit is located contains only 15 ppm Cu.

Belt (1959) has also studied the distribution of sulfophile elements in the rocks and minerals of the Hanover-Fierro stock.

He reports 230 ± 20 and 199 ± 18 ppm Zn in 2 samples of hornblende and 314 ± 31 ppm Zn in one sample of biotite from this stock.

Biotite. Analyses of biotite samples are found in Table 33, and the data are plotted in Figures 31 and 32 according to positions of the samples in the differentiation sequence. Biotite mineral separates are divided in the same three groups as the hornblende samples. The large middle group contains all the biotites from nonporphyritic, subporphyritic and porphyritic granodiorites.

Because chlorite is the most common impurity of the biotite concentrates, the trace element abundance of the chlorite concentrate from A-322b-S and the chlorite-biotite mixture of A-112-N are plotted also in Figures 31 and 32.

Biotite from the main group of relatively unaltered granodiorites, (A-58-S, A-69-P, A-95-N and A-112-N) contains an average of 0.8 ppm silver, 55 ppm cobalt, approximately 35 ppm copper, 42 ppm nickel, 4 ppm lead and 450 ppm zinc. The biotite from the Albion Basin pegmatite contains significantly less cobalt and nickel than the average. The biotite from the mafic layered granodiorite has the same abundance of nickel but significantly more cobalt than the biotites from the main group of granodiorites. Silver and zinc in biotite are less abundant in the Albion Basin pegmatite than in the main group of granodiorites. The scatter of copper values for the biotite samples can not be explained satisfactorily by variations in sample purity, or position in the magma sequence.

Chlorite in sample A-322b-S contains approximately 50

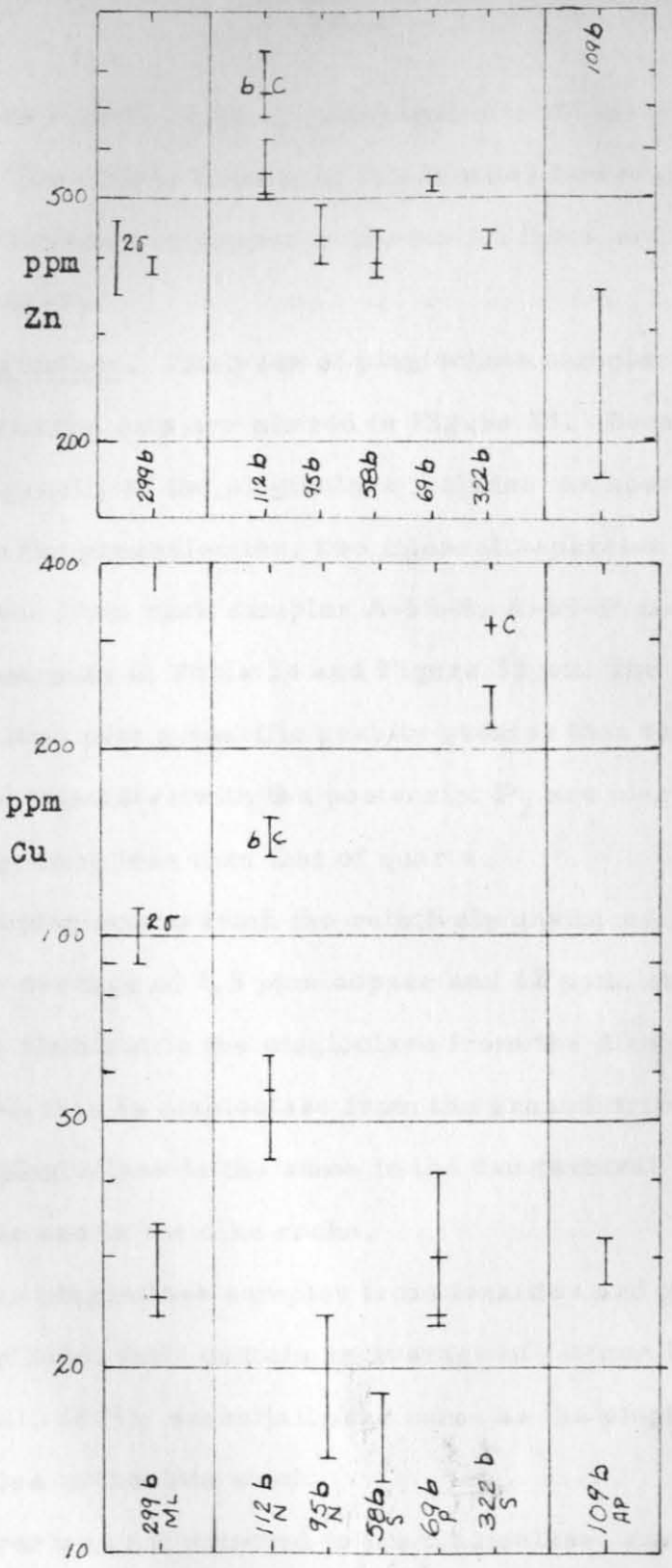


Figure 32. Zinc and copper in biotite. Analyses of the biotite-chlorite mixture from A-112-N (b-c) and the chlorite concentrate from A-322b-S (c) are shown for comparison.

percent more silver, copper, cobalt and nickel than the biotite from this rock. The copper content of this biotite, however, is almost 10 times the abundance of copper in the biotite from porphyritic granodiorite, A-69-P.

Plagioclase. Analyses of plagioclase samples are found in Table 34, and the data are plotted in Figure 33. Because the range in specific gravity of the plagioclase includes the specific gravity of quartz in the granodiorites, two mineral separates of plagioclase were obtained from rock samples A-58-S, A-69-P and A-95-N. Mineral separates in Table 34 and Figure 33 with the postscript P_1 are plagioclase with a specific gravity greater than that of quartz and mineral separates with the postscript P_2 are plagioclase with a specific gravity less than that of quartz.

The plagioclase from the relatively unaltered granodiorites contains an average of 2.5 ppm copper and 12 ppm lead. Copper is much more abundant in the plagioclase from the dike rocks, A-198-AP and A-219-L than in plagioclase from the granodiorite. The lead content of plagioclase is the same in the two textural varieties of granodiorite and in the dike rocks.

Four plagioclase samples from tonalites and granodiorites of the Caledonian suite contain an average of 10 ppm lead (Nockolds and Mitchell, 1948), essentially the same as the plagioclase in the granodiorites of the Alta stock.

Silver was not detected in the plagioclase, and this mineral was not analyzed for cobalt and nickel. A very weak zinc line was

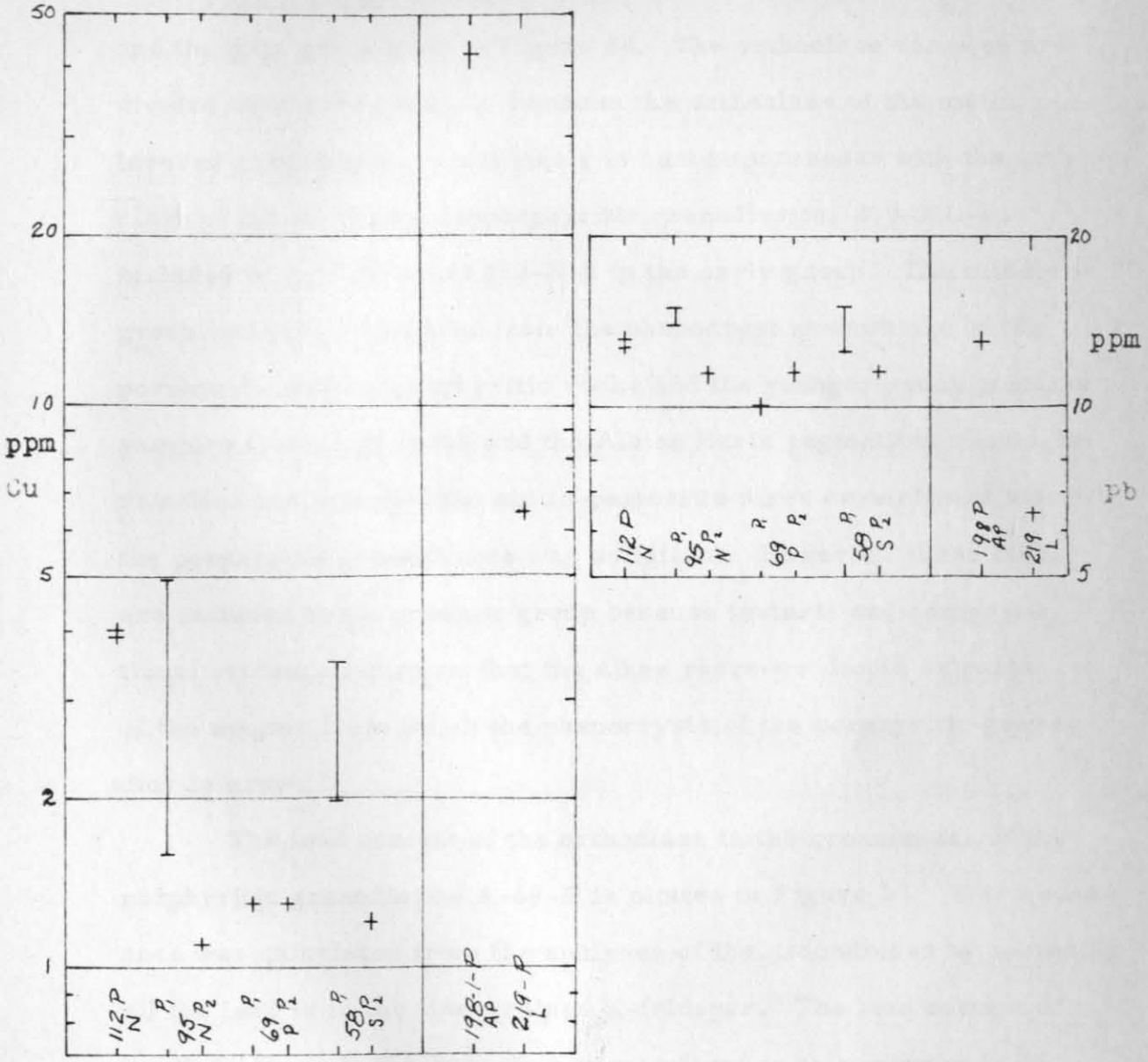


Figure 33. Copper and lead in plagioclase. See Figure 30 for explanation.

seen in 58-S-p_2 but no zinc was detected in the other plagioclase samples.

Orthoclase. Analyses of orthoclase are found in Table 35 and the data are plotted in Figure 34. The orthoclase samples are divided into three groups. Because the orthoclase of the mafic layered granodiorites most likely is contemporaneous with the orthoclase of the enclosing nonporphyritic granodiorite, 299-ML-k is included with 95-N-k and 112-N-k in the early group. The middle group includes orthoclase from the phenocryst assemblage of the porphyritic and subporphyritic rocks and the younger group contains samples from dike rocks and the Albion Basin pegmatite. Geologic relations indicate that the aplite-pegmatite dikes crystallized before the porphyritic granodiorite was solidified. However, these dikes are included in the younger group because textural and compositional evidence indicates that the dikes represent liquid extracts of the magma from which the phenocrysts of the porphyritic granodiorite grew.

The lead content of the orthoclase in the groundmass of the porphyritic granodiorite A-69-P is plotted in Figure 34. This abundance was calculated from the analyses of the groundmass by assuming all the lead is in the fine-grained K-feldspar. The lead content of the K-feldspar in the groundmass calculated in this manner is 44 ppm, the same as it is in the orthoclase phenocrysts in 69-P-k.

The orthoclase of the relatively unaltered granodiorites contains an average of 3.5 ppm copper and 34 ppm lead. The orthoclase in the aplite-pegmatite dikes contains an average of 6.5 ppm

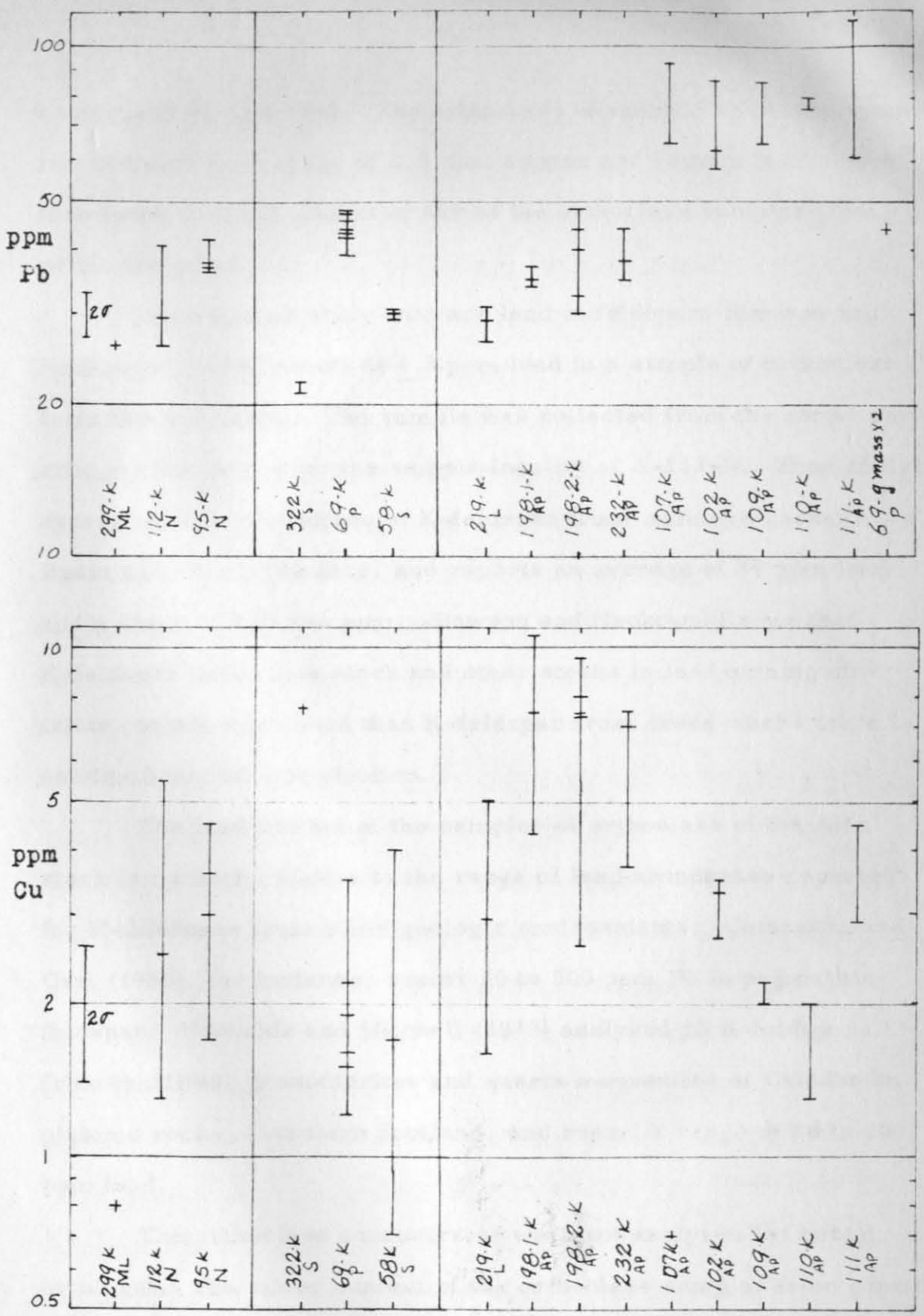


Figure 34. Copper and lead in orthoclase. See Figure 30 for explanation.

copper and 37 ppm lead. The orthoclase of the Albion Basin pegmatite contains an average of 2.5 ppm copper and 78 ppm lead, more than twice the lead content of any of the orthoclase samples from within the stock.

In a regional study on trace lead in feldspar, Slawson and Nackowski (1959) report 44 ± 3 ppm lead in a sample of orthoclase from the Alta stock. The sample was collected from the nonporphyritic granodiorite near the sample locality of A-112-N. They analyzed approximately 90 samples of K-feldspar from intrusive rocks in the Basin and Range province, and reports an average of 39 ppm lead and a range of 8 to 146 ppm. Slawson and Nackowski state that K-feldspar in the Alta stock and other stocks in lead-mining districts contain more lead than K-feldspar from areas where there is no significant lead production.

The lead content of the samples of orthoclase of the Alta stock is not high relative to the range of lead abundances reported for K-feldspars from other geologic environments. Catanzaro and Gast (1960), for instance, report 20 to 500 ppm Pb in pegmatitic feldspar. Nockolds and Mitchell (1948) analyzed 13 K-feldspars from tonalites, granodiorites and quartz monzonites of Caledonian plutonic rocks of western Scotland, and report a range of 10 to 100 ppm lead.

The orthoclase concentrates were not analyzed for cobalt or nickel. The silver content of the orthoclase samples from granodiorite is less than 0.02 ppm. The samples from the aplite-pegmatite dikes, on the other hand, contain approximately 0.1 ppm silver.

The abundance of zinc is less than 30 ppm in all the samples.

Magnetite. Analyses of magnetite are found in Table 36 and the data are plotted in Figure 35. The interpretation of the trace-element data on magnetite is difficult because of the uncertain position of magnetite in the order of crystallization of the minerals in the granodiorite and the lack of control on opaque impurities. There are two textural varieties of magnetite in the granodiorite; it forms euhedra which crystallized with the orthoclase and quartz in the late stage and it also forms euhedra in apparent replacement relation to hornblende and biotite. It is possible that a difference in trace-element composition exists between these two textural varieties of magnetite, and the mineral separates contain magnetite of both types.

Excluding 95-N-m for which there is no control on impurities, magnetite in the main group of granodiorites contains an average of 1.7 ppm silver, 52 ppm cobalt and 53 ppm nickel. The magnetite from A-299-ML contains no detectable lead and approximately 250 ppm zinc. No other samples of magnetite were analyzed for lead and zinc. The copper content of the magnetite samples from the granodiorite range from 47 to 195 ppm. No correlation between copper values and the differentiation sequence is apparent. The highest copper content in magnetite reported in this study is equivalent to the copper content of 0.06 percent chalcopyrite, which could easily be present in the magnetite as an undetected impurity. The leaching studies, described in a later section shed some light

on the nature of the copper in the magnetite separate.

Cobalt and nickel in magnetite are higher in the mafic layered granodiorite, A-299-ML, than in the main group of granodiorites.

Sen et al. (1959) report 10 to 125 ppm Ni and 30 to 60 ppm Co in 5 magnetites from tonalite and granodiorites of the southern California batholith. Rose (1959) reports 200, 300 and 900 ppm Zn in magnetite from granodiorite in the Hanover-Santa Rita Mining area.

Sphene. Analyses of sphene are found in Table 37 and the data are plotted in Figure 36. Sphene samples from the granodiorite contain an average of 58 ppm copper, 100 ppm tin, and 2.3 percent iron reported as ferric oxide. The sphene from the pegmatitic core of the aplite dike at A-353-AP contains 560 ppm tin. Sphene from A-69-P, A-112-N and A-353-AP contain traces of nickel, but in general the samples of sphene do not contain detectable amounts of nickel, cobalt, silver, lead or zinc.

Two fractions of sphene were separated from samples A-69-P and A-112-N. Sample 69-P-s_1 is more magnetic than 69-P-s_2. The sphene of 112-N-s_2 has a lower specific gravity than the sphene of 112-N-s_1. The denser separate from A-112-N and the more magnetitic separate from A-69-P have the higher iron content in the two pairs. The tin content of the sphene is plotted against the iron content of the mineral in Figure 37, and a weak positive correlation is evident.

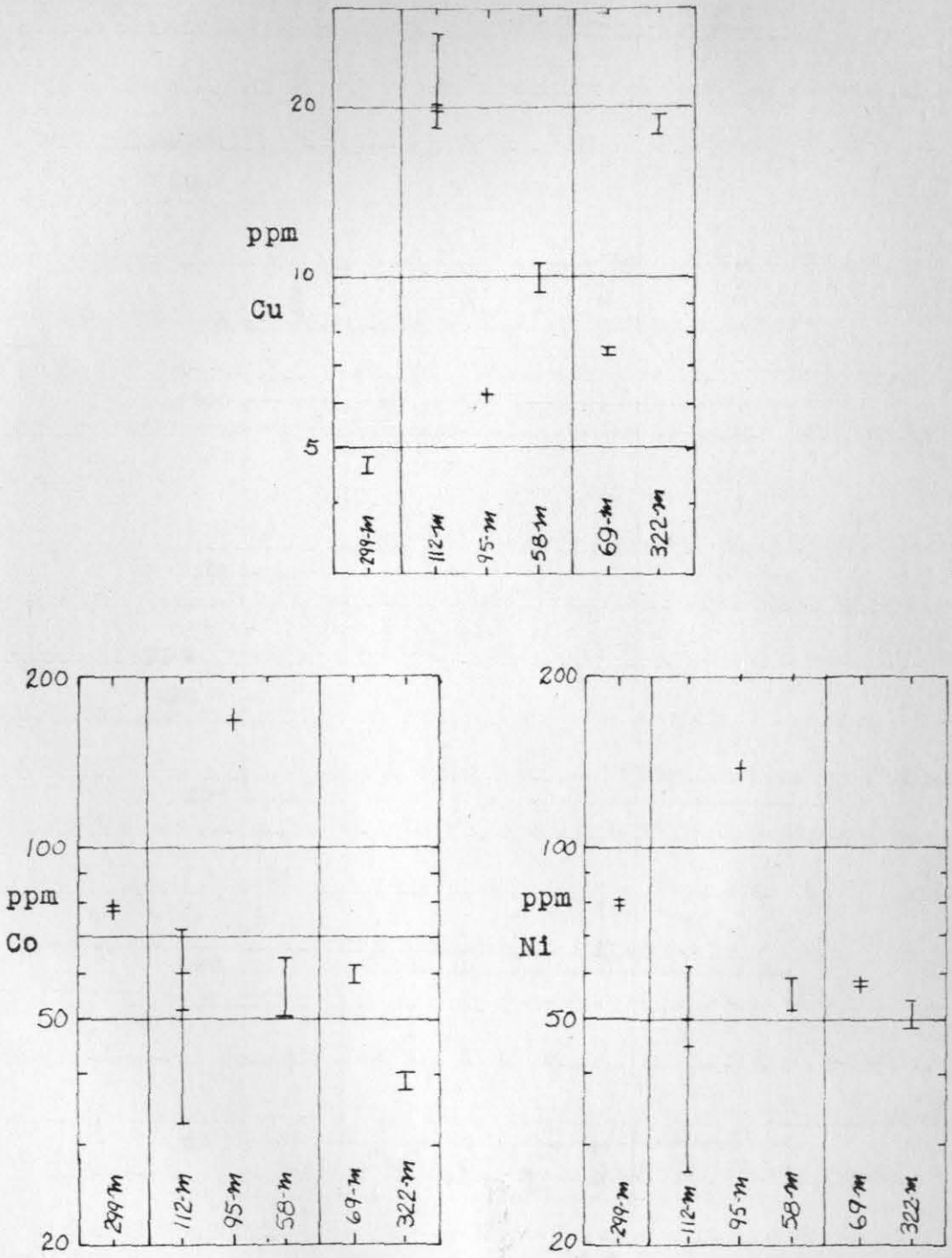


Figure 35. Copper, cobalt and nickel in magnetite.

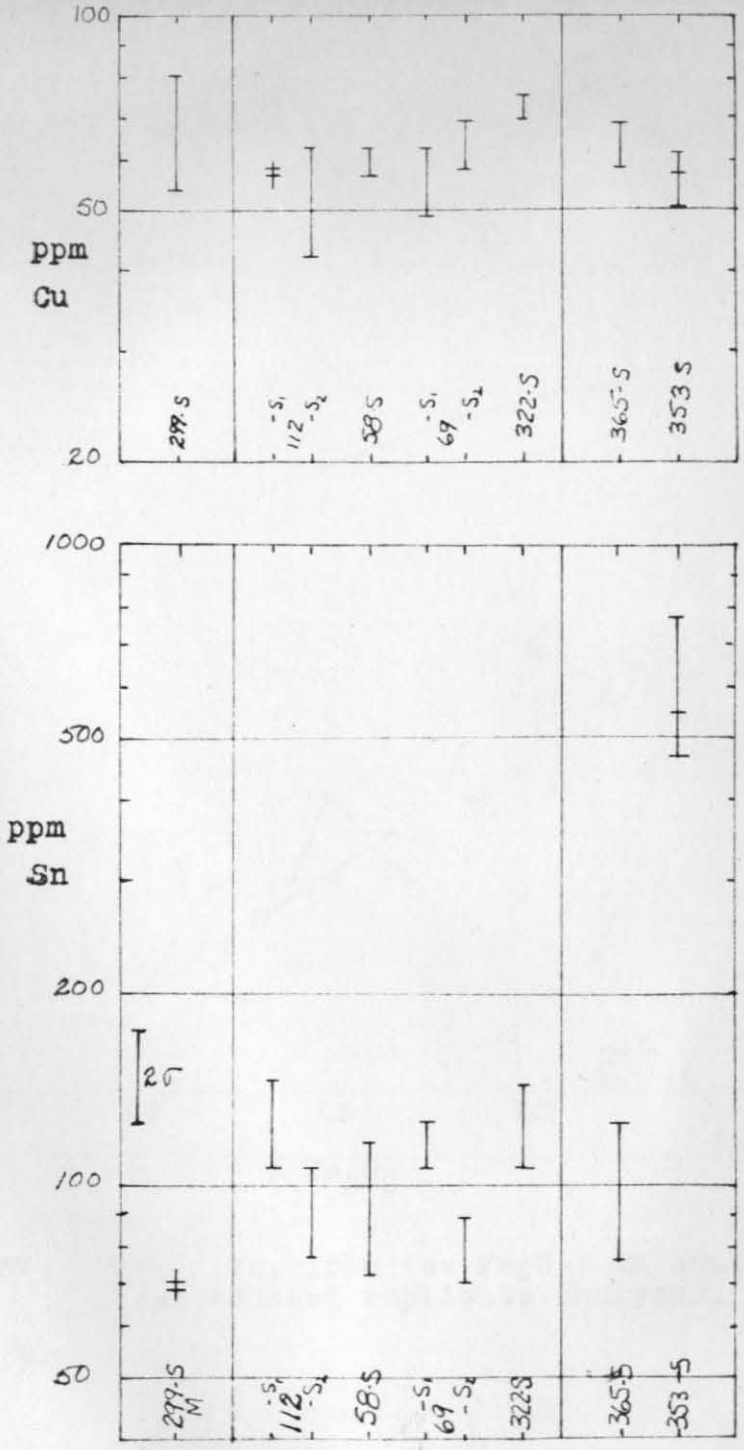


Figure 36. Copper and tin in sphene. See Figure 30 for explanation.

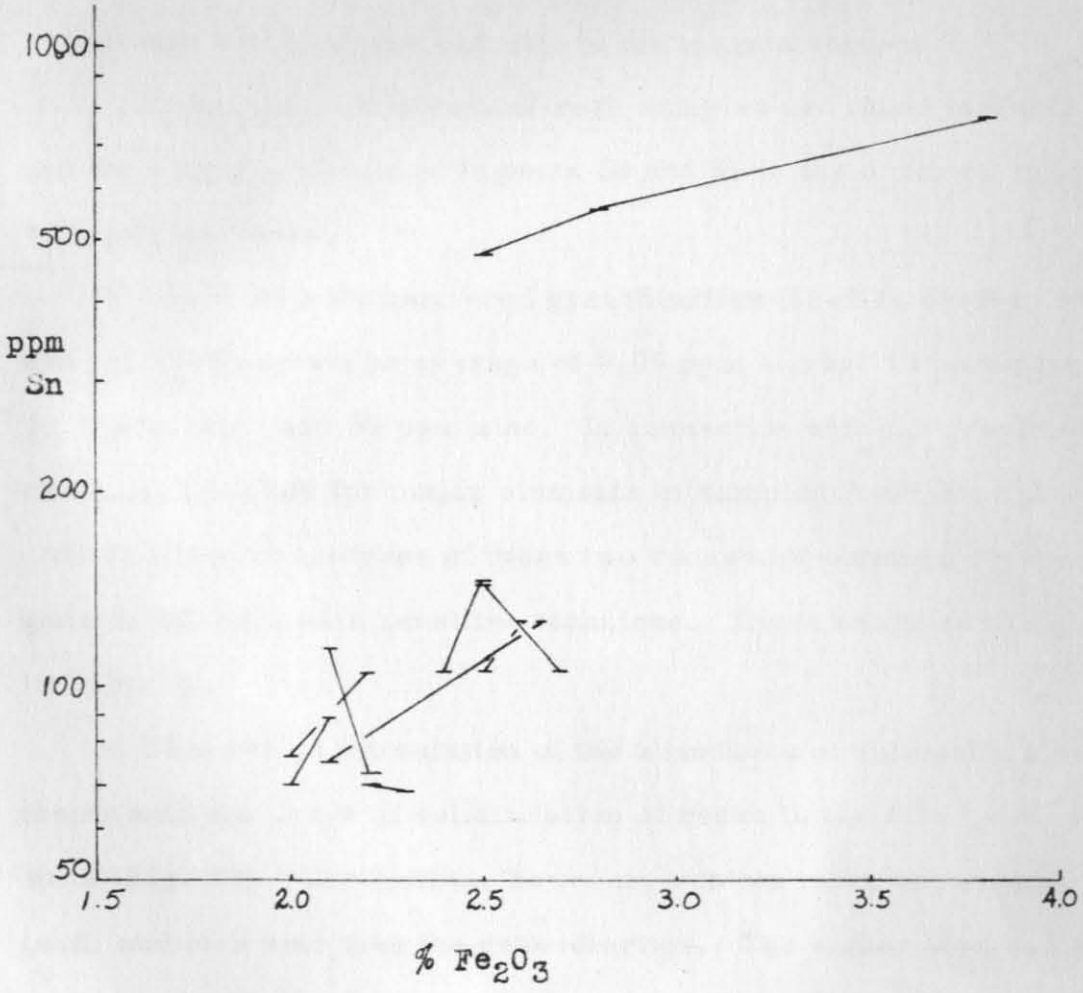


Figure 37. Tin vs. iron (as Fe_2O_3) in analyses of sphene. Lines connect replicate analyses.

The abundance of copper in sphene is the same in all samples analyzed, which is surprising because the suite of sphene samples represents every recognized step in the magma sequence.

Total rock. Analyses of rock samples are found in Table 38 and the data are plotted in Figures 38 and 39 in the order of solidification of the rocks.

The relatively unaltered granodiorites (58-S-t, 69-P-t, 95-N-t and 112-N-t) contain an average of 0.05 ppm silver, 13 ppm copper, 10.5 ppm lead, and 55 ppm zinc. In connection with the gravimetric chemical analyses for major elements of samples A-69-P and A-112-N trace-element analyses of these two rocks were obtained by a more general although less sensitive technique. These analyses are given in Table 40.

There is no correlation of the abundance of sulfophile elements with the order of solidification of rocks in the Alta igneous suite (Fig. 29). The aplites, however, contain more copper and lead, and less zinc than the granodiorites. The higher lead content is due to the more abundant orthoclase in the aplites. The higher copper content can not be explained on the basis of differences in mineralogy. The mafic minerals, which contain most of the copper in the granodiorite, are practically lacking in the aplite-pegmatite dikes.

Within the group of granodiorites there is no correlation of metal content to the texture of the rock; there is, however, a positive correlation of metal content and alteration.

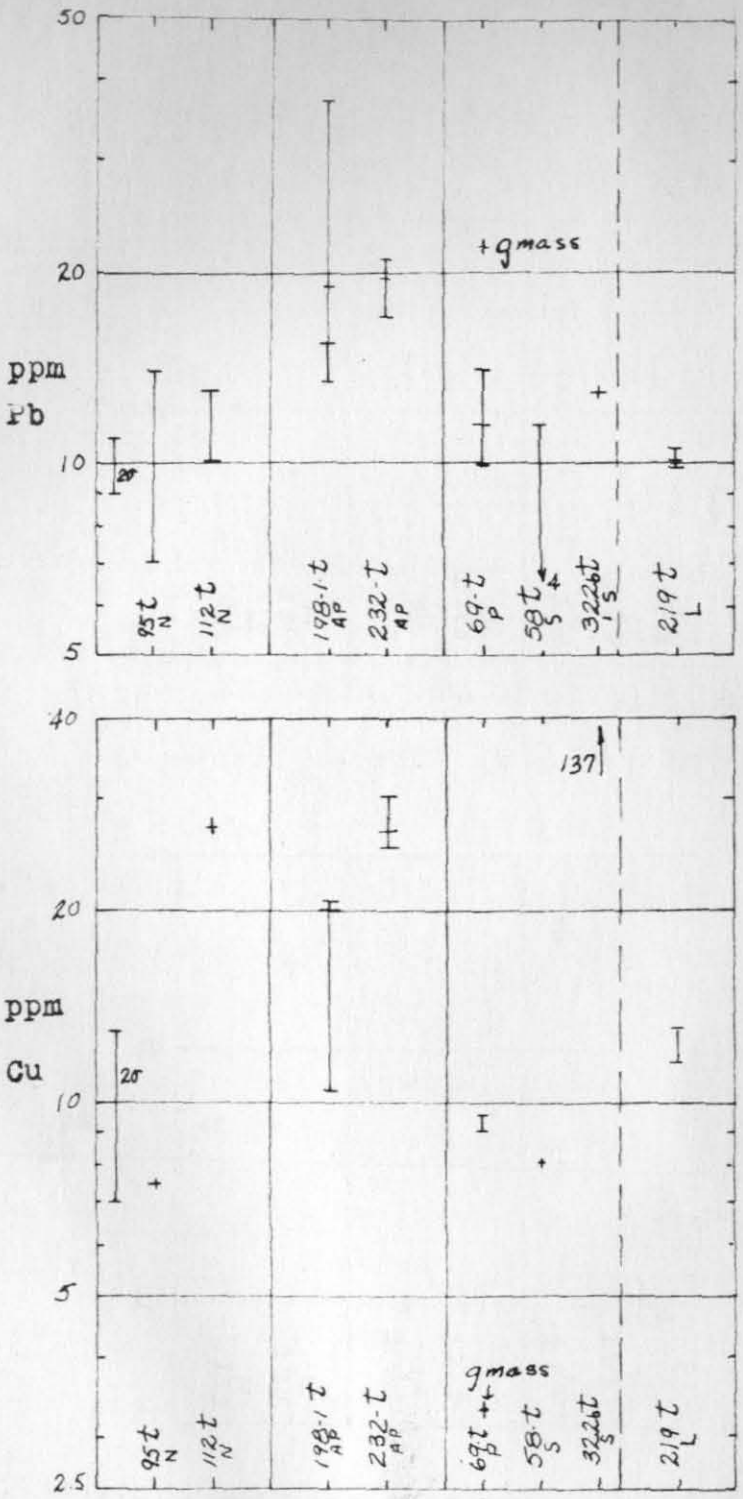


Figure 38. Lead and copper in total rock. See Figure 30 for explanation.

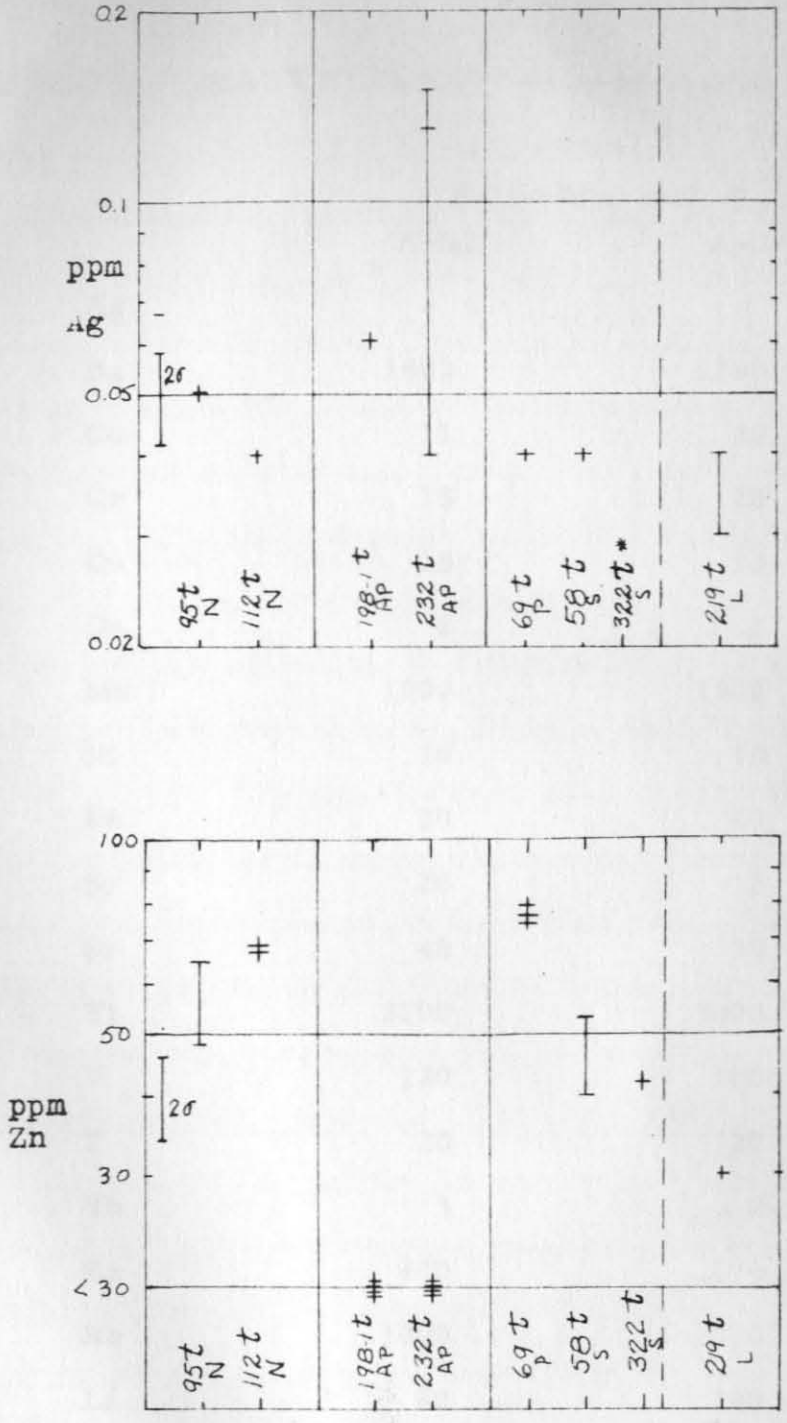


Figure 39. Silver and zinc in total rock. See Figure 30 for explanation.

TABLE 40. TRACE ELEMENTS IN A-69-P AND A-112-N

ppm

E. Godijn, analyst

	A-112	A-69
Ag	-	-
Ba	1800	1700
Co	11	20
Cr	15	20
Cu	15	10
Ga	2	2
Mn	1000	1000
Ni	10	10
Pb	30	40
Sc	20	12
Sr	40	30
Ti	3000	3000
V	120	100
Y	20	20
Yb	3	2
Zr	400	170
Rb	1000	2000
Li	80	100
Zn	-	-

Sandell and Goldich (1943) report the average copper content of 29 igneous rocks to be 21 ppm with a range from 3 to 140 ppm. Wedepohl's (1953) average for the zinc content of 70 acidic igneous rocks is 45 ppm with a range of 7 to 210 ppm. Goldschmidt (1954) reports a range of 5 to 50 ppm with an average of 24 ppm for the lead content of granites and rhyolites. Relative to these averages, the copper content of A-112-N and A-69-P (Table 40) is low, the zinc content is slightly above average (Table 38), and the lead content is also slightly above average (Table 40).

Belt (1960) has studied the distribution of copper and zinc in the Hanover-Fierro stock of granodiorite in the Central mining district, New Mexico. Ore deposits associated structurally with the stock are magnetite replacement deposits and replacement deposits of zinc with minor amounts of copper and lead. The Santa Rita porphyry-copper deposit is located two miles southwest of the Hanover-Fierro stock. Belt reports 51 $\pm$ 13 ppm copper and 43 $\pm$ 5 ppm zinc for the relatively unaltered rock in the stock. The range of all analyses is 11 to 273 ppm for Zn and 4 to 645 ppm for Cu. Zinc anomalies and most of the copper anomalies are found in altered rock and areas near or adjacent to ore bodies or mineralized zones. The relatively unaltered granodiorite of the Alta stock has approximately the same zinc but much less copper than the relatively unaltered granodiorite of the Hanover-Fierro stock.

The data on the average sulfophile element content of minerals of relatively unaltered granodiorite are summarized in Table 41. The analytical data on minerals and rocks of samples A-58-S,

TABLE 41. AVERAGE ABUNDANCE OF SULFOPHILE ELEMENTS IN RELATIVELY UNALTERED GRANODIORITE OF THE ALTA STOCK

ppm

	Ag	Co	Cu	Ni	Pb	Sn	Zn
Total rock	0.05	(12)[a]	13	(10)[a]	10.5	*	55
Plagioclase	< 0.05	*	2.5	*	12	*	< 30
Hornblende	(1.0)	35	10	25	< 5	< 15	≤ 300
Biotite	(0.8)	50	35	42	4	< 15	450
Orthoclase	< 0.05	< 1	3.5	< 0.5	34	< 10	< 30
Magnetite	(2.0)	52	100	55	*	< 15	*
Sphene	< 1	< 20	58	< 5	< 10	100	< 70

* Not determined.

(a) Table 40.

Doubtful numbers in parentheses.

A-69-P, A-95-N and A-112-N were used to compute the averages.

As a check on the analytical method and to estimate the metal content of the unanlyzed minerals, the contribution of each of the analyzed minerals toward the trace-element content of the total rock is calculated. The sum of these contributions is compared to the analysis of the whole rock. This procedure was carried out on the minerals of samples A-69-P, A-112-N and A-198-AP and the results are shown in Table 42. The summation for lead is very good in all three cases, and for zinc it is fair. The summation of the silver content of the minerals of A-69-P and A-112-AP is four times the abundance of silver reported for the rocks. This discrepancy indicates an error in the analytical method for silver in the analyses of mafic minerals. The summation for copper in minerals is approximately 50 percent of the amount reported in the rock analyses. Attributing all this excess copper to likely host minerals in the group of unanalyzed minerals in the rock, mainly plagioclase alteration minerals and chlorite, gives an abundance of copper in these phases of 100 ppm in the case of A-69-P, 450 ppm in the case of A-112-N and 1000 ppm in the case of A-198-1-AP. The excess copper need not be in these alteration minerals, however. It may be present as undetected trace minerals.

Leaching experiments. Two groups of leaching experiments were made. In the first group, portions of the 100-mesh to 200-mesh size fraction of the orthoclase separate of the pegmatitic core of the aplite dike at A-198-2-AP were leached with nitric acid under nine sets of conditions of time and acid concentration. The samples

TABLE 42. CONTRIBUTION OF METAL CONTENT OF ANALYZED MINERAL TO THE METAL CONTENT OF ANALYZED ROCKS

A-69-P

	wt %	ppm					
		Ag	Co	Cu	Ni	Pb	Zn
Sum of minerals	97.2	0.16	7.4	6.6	6.65	11.75	(40)[a]
69-P-t	100	0.04	(12)[b]	9.0	(10)[b]	12	70
Δ	- 2.8	+ 0.12	- 4	- 2.4	- 4	--	--

Minerals not analyzed: 0.3% apatite, 0.25% zircon, 1.0% chlorite and 1.3% cericite.

A-112-N

	wt %	ppm					
		Ag	Co	Cu	Ni	Pb	Zn
Sum of minerals	96.4	0.18	7.1	13.2	4.85	11.8	64
112-N-t	100	0.04	(12)[b]	27	(10)[b]	12	68
Δ	- 3.8	+ 0.14	- 5	- 15	- 5	--	--

Minerals not analyzed: 0.4% apatite, 0.8% zircon, 0.55% chlorite and 2.75% sericite.

A-198-1-AP

	wt %	ppm		
		Ag	Cu	Pb
Sum of minerals	98.8	0.03	14	16.8
198-1-AP-t	100	0.06	25	17
Δ	1.2	- 0.03	- 11	--

Minerals not analyzed: 0.5% hematite, 0.2% biotite, 0.1% chlorite and 0.2% sphene.

a. Magnetite and hornblende not analyzed for zinc.

b. Analyzed by another method, Table 40.

were agitated a few times during the acid treatment. After the treatment the samples were washed with distilled water dried and analyzed for copper and lead. The description of the treatment and the data are found in Table 43. All the analyses of leached samples shown in this table were made on the same plate. The high silver values in the leached samples are undoubtedly due to contamination from the nitric acid. Despite the lack of adequate control and the possibility of contamination from the reagents, the results do show that copper and possibly some lead are very loosely held in this orthoclase.

The second group of experiments consisted of treating rock samples and plagioclase, orthoclase, biotite and magnetite mineral separates with individual acid leaches and comparing the analysis of the leached sample with the average for analyses of untreated parallel aliquots.

Table 44 shows the data on the leaching of feldspars and total rock. With the exception of 69-P-t, the samples lost an average of 30 percent copper in the leaching process. With the exception of whole rock sample from the aplite-pegmatite dike, 198-1-AP-t, no appreciable lead was removed from the mineral separates or rock samples.

Table 45 summarizes the leaching experiments on the biotite from A-112-N and the magnetite from A-299-ML. Both HNO_3 and HCl were used in the experiments. Copper and zinc were selectively removed from the magnetite. The data of the behavior of

TABLE 43. DATA ON LEACHING EXPERIMENTS ON 198-2-AP-k

ppm Pb[a]

Time, hr	Distilled H_2O	Conc. HNO_3 0.1N	0.5N	2.0N	8N
1/6	39			38	
1/2				36	
1				38	
3-1/2		40	35	35	33
28				38	

ppm Cu[a]

Time, hr	Distilled H_2O	Conc. HNO_3 0.1N	0.5N	2.0N	8N
1/6	4.6			4.8	
1/2				3.6	
1				6.7	
3-1/2		4.4	3.9	3.7	3.6
28				3.6	

(a) Unleached sample of 198-2-AP-k contains 39 ± 6 ppm Pb and 6.9 ± 1.6 ppm Cu.

TABLE 44. LEACHING EXPERIMENTS ON PLAGIOCLASE, ORTHOCLASE AND TOTAL ROCK IN 2.0 N HNO_3 FOR FOUR HOURS

	Cu ppm				Pb ppm			
	Untreated		Leached		Untreated		Leached	
Sample	1	2		$\Delta^{(a)}$%	1	2		$\Delta^{(a)}$ %
198-1-AP-k	7.4		5.5	-25	35.5		31.5	-10
198-1-AP-p	42		25.2	-40	13		14.5	+11
198-1-AP-t	22	21	14.3	-30	17.1	15.5	10.2	-41
69-P-k	2.0	1.6	1.4	-30	44	48	50	+12
69-P-p	1.3		8	-38	11		9.3	-15
69-P-gmass	3.3		2.3	-30	22		23.5	+ 7
69-P-t	9	9.5	10.5	+16	12.0	11.5	13.5	+12
112-N-5	27		20.0	-26	12		13	+ 8
232-AP-t	30	26.5	16	-47	18	20	17	- 6
110-AP-k	1.6		0.93	-42	78		78	0
Ave Δ%				-29				- 2.2
Rel. s.d.%				12				10

Column
1 Average abundance from all analyses.
2 An analysis on same plate as leached samples.

(a) Maximum difference between leached and unleached samples.

TABLE 45. LEACHING EXPERIMENTS ON BIOTITE AND MAGNETITE

Sample	Treatment	ppm Cu	Zn	Ag	Co	Ni
Biotite 112-N-b	Untreated	53	500	0.7	41	34
	3 min in 2.5 N HCl, 8 min wash in dist. water	36	470	0.5	35?	29?
	6.5 hr in 2.0 N HNO_3	27	315	0.35	34	38
	6.5 hr in 3.5 N HCl	15	425	0.6	53	43
Magnetite 299-ML-m	Untreated	46	*	1.8	78	80
	18 hr 2.0 N HNO_3 [a] + 4 hr Conc. HNO_3	35	*	1.7	68	70
	24 hr 2.5 N HCl [b]	36	*	1.7	74	85

* Not determined.

(a) 0.65% of sample was dissolved in this treatment.

(b) 4.25% of sample was dissolved in this treatment.

silver, cobalt and nickel are not conclusive. Copper in biotite and magnetite is apparently more soluble in 2.5 N HCl than in 2.0 N HNO_3, but the nitric acid is a better leaching agent for zinc and silver. The decrease in copper content with increase leaching time indicates that the copper is being removed from the biotite structure faster than the mineral is going into solution.

Only 0.35 percent of the magnetite sample was taken into solution with 2.0 N nitric acid in 18 hours. This puts an upper limit of 0.04 weight percent on the contamination of the sample with iron filings during the crushing process.

Tauson and Kravchenko (1956) performed leaching experiments on rocks and minerals from granitic rocks. They boiled 0.5 gm of the rock or mineral sample for one hour in 100 cc of 1:50 HCl which contained 1 g/l of NaCl. They found that 40 percent of the lead and 80 percent of the zinc in the rock samples was removed by this leaching procedure. From 70 to 80 percent of the zinc in the biotite was removed by leaching but only 12 to 18 percent of the lead in the K-feldspar was removed by this procedure. Tauson and Kravchenko conclude that this "extrasilicate" metal was probably in the silicate lattice initially but exsolved on cooling, forming inclusions of PbS or native Pb, but did not move outside the grain boundaries.

Summary

Cobalt and nickel. Most of the cobalt and nickel in the average unaltered granodiorite is probably in the crystal structure of hornblende, biotite and magnetite. Hornblende and probably biotite

completed crystallization at an early stage in the history of the Alta stock; a stage which was characterized by free interchange of liquid and crystals from all parts of the magma chamber. Under this condition, no fractionation of cobalt and nickel in hornblende and biotite would be expected in the main group of granodiorites and none was found. The hornblende and biotite of the mafic layered granodiorite are earlier than the hornblende and biotite of other granodiorites and have a slightly higher cobalt and nickel content than the average for the other granodiorites. This suggests that the abundance of cobalt and nickel in the liquid part of the magma decreased with time in the early stages of the Alta stock. The still lower cobalt and nickel abundance in the hornblendite veinlet and in the biotite from the Albion Basin pegmatite also suggests a decrease of available cobalt and nickel during the crystallization of the Alta stock. Determination of major element abundances, especially magnesium and iron, in hornblende and biotite would aid in the interpretation of these trends.

Except for the high values in 95-N-m and 198-1-AP-m, the distribution of cobalt and nickel in magnetite supports the trend suggested for these elements above.

Some cobalt and nickel is present in the granodiorite in chlorite and judging by the two analysis 112-N-bc and 322-S-c, the process by which biotite was altered to chlorite also added cobalt and nickel to the rock.

Copper. In the average least altered granodiorite of the stock, approximately 50 percent of the copper is in the magmatic

minerals, 20 percent is in the alteration minerals, largely chlorite, and 30 percent is loosely held in the rock in a form which is soluble in cold dilute nitric acid. The analyses of the two chlorite concentrates show that, like cobalt and nickel, copper was added to the solid phases of the rock during the replacement of biotite by chlorite. Because the average granodiorite of the Alta stock has much more chloritic alteration than the rocks used in this study, the stock as a whole contains more copper than the average shown in Table 40.

The trends in copper content established during magmatic crystallization have been masked subsequently by this alteration. The scatter of values for copper in hornblende, biotite and magnetite is probably due to very small inclusions of copper-rich minerals added to the rock at a late stage. The narrow spread of values for the abundance of copper in the suite of sphene samples, suggests that no fractionation in copper took place from the earliest stage of crystallization of the granodiorites to the late-stage derivation of the pegmatite dikes and the hornblendite veinlets. On the other hand, the very high copper content of plagioclase from the aplite-pegmatite dike A-198-AP, suggests that copper was more abundant in the fluid which formed this pegmatite than the magma which crystallized to form the plagioclase in the granodiorite.

Lead. The lead content of the granodiorite of the Alta stock is divided almost equally between plagioclase and orthoclase. Very little lead is contributed by the mafic minerals, or by the deuteric alteration minerals. Essentially no significant lead is present in the granodiorite as loosely held material as in the case of copper.

In the aplite dikes, however, the leaching experiments show that some of the lead is present in an acid soluble form.

The variation of lead content of orthoclase among the orthoclase samples is almost within the experimental error of the method, and what variations do exist are not related in an obvious way to the differentiation sequence. This suggests that lead was not fractionated during crystallization of the Alta magma. The suite of orthoclase samples is the most complete and well-documented sample sequence used in this study. The lack of a trend in this suite can be explained by one of the following hypotheses.

(1) The proposed mechanism for differentiation of the magma was too inefficient to cause measurable fractionation of the trace elements.

(2) Orthoclase was saturated with respect to lead for the physical and chemical conditions of the magma.

(3) Another variable in the magma had a strong control on the abundance of lead in the crystalline phases.

The detailed zoning in the feldspars, the geologic relations between nonporphyritic and porphyritic phases of the granodiorite, the similarity in composition of the groundmass of the porphyritic granodiorite to the composition of the aplite dikes are good evidence that crystal fractionation and liquid differentiation did occur in the Alta magma. There is no proof in these arguments, however, that the differentiation affected the distribution of trace elements. Therefore a fruitful continuation of this study would be to analyze the mineral separates for other elements and determine if fractionation

has affected the distribution of any of the nonsulfophile trace constituents. On the basis of ionic size and charge, lead should follow barium, strontium and large divalent ions of other trace elements during differentiation and trace element fractionation. If the abundance of these other trace elements should show a trend in the sequence of orthoclase samples, the fractionation of lead would be better expressed in terms of ratios with these trace elements, such as lead/barium or lead/strontium.

Even if there is a well-defined trend in these ratios which is correlative with the magmatic sequence, then the constancy of lead in orthoclase samples from relatively unaltered granodiorite and aplite-pegmatite dikes in the stock, requires an explanation. In addition, the relatively high values of lead in orthoclase from the Albion Basin pegmatite pod must be explained.

One possibility that may explain both of these features of the distribution of lead is that changes in the sulfur content of the magma may have strongly influenced the distribution of lead between magma and growing orthoclase crystals. The most important variable governing the availability of an element for substitution in a mineral in most cases is the abundance of the element in the magma. However, the form in which the metal is present in the magma is very important also. Warren and Pincus (1940) and Forland and Weyl (1954) have shown with X-ray studies in glasses, there is considerable preorganization of some constituents in a silicate melt prior to crystallization. In the melt, Si-O bonds are strong and lead to polymerization of SiO_4 groups. The only

difference between the structure of glasses and the structure in a liquid is that in the melt, these bonds are continually breaking and reforming. This short-term order is also applicable to the more metallic elements. The metals with a noble gas structure tend to be surrounded by the relatively nondeformable oxygen atoms, whereas the sulfophile cation with a nonnoble gas type structure are surrounded by deformable anions, principally sulfur. The ability of a sulfophile element to enter into a silicate lattice, then, will depend not only on the size and charge of the ion, but also on how strongly the metal is bonded to the surrounding sulfur atoms in the melt. This in turn will depend on the relative abundance of sulfur and metal in the magma and on the strength of the metal-sulfur bond. In a differentiating magma in which some sulfophile elements, but no sulfur, are entering the solid phases, the sulfur-metal ratio will increase and the sulfophile elements in the later liquids will be more closely associated with sulfur than in the earlier phases of the magma. A closer association of sulfur and metal would decrease the abundance of a sulfophile element which would leave the magma and enter the oxygen-rich environment of the silicate and oxide minerals. Metal-sulfur complexes would give the crystals of a mineral growing from melts with relatively high sulfur-metal ratio a lower sulfophile element content than the crystals of the same mineral growing from a melt with a lower sulfur-metal ratio.

In the case of the Alta stock, no pyrite crystallized until the pegmatitic stage in the formation of the aplite dikes. Therefore the sulfur content of the liquid part of the magma must have been

increasing with time during crystallization of the granodiorites. Consequently the constancy of lead abundance in orthoclase and plagioclase may indicate that lead was preferentially concentrated in the liquid portion of the magma during crystallization of the granodiorite.

The sulfur-lead ratio of a melt can be decreased in two ways, by crystallization of pyrite or by preferential entry of sulfur into a vapor phase. If the Albion Basin pegmatite was emplaced after a gas phase had desulfured the liquid silicate portion of the magma, the higher lead in the orthoclase samples from the pegmatite may be the result of a lower sulfur-lead ratio rather than a higher abundance of lead in the pegmatitic liquid.

Silver. The low abundance of silver in the granodiorite reflects not only its rarity but also the strong sulfophile character of this element. The silver abundances for minerals and whole rockswhich are internally consistent data, probably represent either metal in the silicate lattice, metal in undetected trace minerals, or metal which was adsorbed on to grain boundaries at a late stage. In any case, the lack of detectable silver in the whole-rock analyses of the granodiorite and the presence of detectable silver in the later dikes, points to concentration of silver in the liquid phase of the magma during differentiation where it is most likely bonded very strongly to sulfur.

Tin. The lower than average abundance of tin in sphene from the mafic layered granodiorite and the much higher than average abundance of tin in the pegmatite dike show that tin was

preferentially concentrated in the residual liquid in the Alta stock.

Zinc. At least 50 percent of the zinc in the granodiorites is in the biotite. Possibly 25 percent is in the hornblende, and some zinc is undoubtedly in the magnetite. Because zinc is present only in the mafic minerals, for which the differentiation sequence is poorly defined, the trend for zinc in the differentiation series of the Alta magma is not apparent. The lower-than-average zinc content of the biotite from the Albion Basin pegmatite suggests that zinc was preferentially concentrated in the crystalline phases during crystallization of the Alta magma. The very high (770 ppm) abundance of zinc in the chlorite-biotite mixture from A-112-N suggests that zinc was added to the granodiorite during deuteric alteration.

CONCLUSIONS

The purpose of this study was to determine if the phenomena of crystallization of the igneous rocks of the Alta stock are continuous with the phenomena of generation of an ore-forming fluid. The crystallization history and the trace-element trends can be evaluated in terms of the classical hypothesis for the origin of hydrothermal ore deposits.

Generally, it is agreed that primary metalliferous veins, such as those of the Park City-Cottonwood area, are genetically related to intrusive igneous rocks. There is disagreement on the details of the relation, and in most mining districts the field relations demonstrate only that both magma and ore-forming fluid originated at depth.

The classical view, based largely on theoretical considerations, holds that "ore-metals and mineralizers" present in minute proportions in the original melt are concentrated in the residual liquid by fractional crystallization of rock-forming minerals devoid of these substances and that during a late stage in the solidification history of the intrusion the rest liquid escapes to form ore deposits.

Fractional crystallization was a major factor in the solidification of the Alta stock. The stock crystallized from the walls toward the center and in a late stage the partially solidified core, which contained a liquid rich in alkalis, silica and volatiles was intruded into the previously crystallized upper portions of the stock. Volatiles were lost from the intruded mass and the magma crystallized to a rock with a porphyritic texture.

The spatial relation of ore deposits to the Alta stock and other igneous rocks in the Park City-Cottonwood area has been noted by many, and was used by Butler (1915) as the principal example for his apical theory of the location of ore deposits. The geologic work in this study has shown that the spatial relation in the instance of the Alta stock is much closer than was previously realized. The location and orientation of the Flagstaff-Emma ore zone, which has yielded approximately 30 percent of the combined production of the Big Cottonwood and Little Cottonwood districts, may be structurally controlled by the late-stage emplacement of the volatile-rich magma which crystallized to form the porphyritic granodiorite.

Allowing for the possibility of large interlaboratory analytical errors, the abundancesof Cu, Co, Ni, Pb and Zn in minerals of the Alta stock are not very much different from the abundances of these elements in the same minerals from similar rocks from geologic environments which do not contain significant ore deposits.

The variations in metal content of the minerals within the Alta igneous suite are not related in an obvious way to the differentiation sequence. The evidence suggests, however, that Cu, Pb, Ag and Sn may have been slightly more abundant in the late-stage magmatic phases of the Alta stock. The data are inconclusive on the trend of zinc during the magmatic crystallization. Cobalt and nickel decrease in the differentiation series.

Two analyses of chlorite concentrates indicate that Cu, Co, Ni, Ag, and Zn are added to the solid phases of the rock during alteration of biotite to chlorite. A detailed study of alteration was not made, but presumably the chlorite is the product of deuteric alteration, and the high metal abundance in chlorite may reflect the high metal abundance of the fluid which caused the alteration. If this fluid represents the late-stage rest liquid from the crystallization of the Alta stock then the relation of the Alta stock to the ore deposits conforms to the classical hypothesis of the relation of igneous rocks to ore deposits. This relation can not be inferred on the basis of the trace-element trends in the primary magmatic phases of the stock.

There are many logical continuations of this study. Continued geologic studies might improve the suggested structural

relation between the porphyritic granodiorite and the Flagstaff-Emma ore zone. Additional trace-element studies however should not be initiated without a detailed study of alteration in the stock. Specifically, the relation between rock type and abundance, trace-element content, and mineralogy of the alteration minerals is important. The effect of the alteration on the trace-element content of the unaltered phases must also be studied. The comparison of the chemical and mineralogic effects of the pervasive but generally weak alteration in the Alta stock with the chemical and mineralogic changes produced by hydrothermal alteration near veins which locally crosscut apophyses of the stock, may provide information on the composition of the altering solutions in these two presumably different environments.

Although this initial investigation on the abundance of elements in minerals was not as fruitful as would be desired, continued research with improved analytical procedure may yield rewarding results. The technique should be broadened in order to measure the abundance of zinc at low concentration and copper with more precision. It would be very desirable to study S, F and Cl in addition to the heavy metals in minerals such as apatite and biotite.

The question of whether a specific ore body was derived from a specific igneous rock cannot be answered by the methods used in this study. Comparison of the isotopic composition of the lead in the minerals of the ore deposits of the Flagstaff-Emma ore zone with the isotopic composition of lead in rocks and minerals of the Alta igneous suite may provide an answer to this question.

Similar studies in igneous rocks which are not spatially

associated with ore deposits may provide information on what aspects of the intrusive, structural and hydrothermal history of a metalliferous area are most important for the formation of ore deposits. Such studies may ultimately determine whether it is the initial abundance of metal and volatiles in the magma, the bulk composition of the magma, the crystallization processes, the structural relations of the igneous rocks to the intruded sediments, the physical and chemical properties of the host rock, depth of intrusion or some other characteristic of the system which is critical to the formation of ore deposits in and near one group of igneous rocks and not near another group.

BIBLIOGRAPHY

Baker, A. A., B. J. Sharp and M. D. Crittenden, 1952, GEOLOGIC MAP OF THE AREA SOUTH OF PARK CITY, UTAH: U.S. Geol. Survey, open file map.

Belt, C. B., Jr., 1959, INTRUSION AND ORE DEPOSITION IN NEW MEXICO: Unpublished Ph.D. Thesis, Columbia University.

Belt, C. B., Jr., 1960, INTRUSION AND ORE DEPOSITION IN NEW MEXICO: Econ. Geol., v. 55, p. 1244-1271.

Boutwell, J. M., 1913, GEOLOGY AND ORE DEPOSITS OF THE PARK CITY DISTRICT, UTAH: U.S. Geol. Survey Prof. Paper 77, 231 p.

Boutwell, J. M., 1924, GEOLOGIC MAP HEAD OF THAYNES CANYON SHOWING CRESCENT ZONE: 1:4800 unpublished map of United Park City Mining Co., Park City, Utah.

Butler, B. S., 1915, RELATIONS OF ORE DEPOSITS TO DIFFERENT TYPES OF INTRUSIVE BODIES IN UTAH: Econ. Geol. v. 10 p. 101-122.

Calkins, F. C. and B. S. Butler, 1943, GEOLOGY AND ORE DEPOSITS OF THE COTTONWOOD-AMERICAN FORK AREA, UTAH: U.S. Geol. Survey, Prof. Paper 201, 152 p.

Campbell, R. B., 1959, THE TEXTURE, ORIGIN, AND EMPLACEMENT OF THE GRANITIC ROCKS OF GLENLYON RANGE, YUKON, CANADA: 299 p., unpublished Ph.D. Thesis, California Institute of Technology.

Catanzaro, C. J. and P. W. Gast, 1960, ISOTOPIC COMPOSITION OF LEAD IN PEGMATITIC FELDSPARS: Geochim. et Cosmochim. Acta, v. 19, no. 2, p. 113-126.

Chayes, F., 1956, PETROGRAPHIC MODAL ANALYSIS: John Wiley and Sons, New York, 113 p.

Crittenden, M. D., B. J. Sharp and F. C. Calkins, 1952, GEOLOGY OF THE WASATCH MOUNTAINS EAST OF SALT LAKE CITY, PARLEYS CANYON TO TRAVERSE RANGE: Utah Geol. Soc. Guidebook, no. 8, p. 1-37.

Dieke, G. H. and H. H. Crosswhite, 1943, THE USE OF IRON LINES AS INTENSITY STANDARDS: Jour. Opt. Soc. Am., v. 33, p. 425-434.

Dixon, W. J. and F. S. Massey, Jr., 1957, INTRODUCTION TO STATISTICAL ANALYSIS: McGraw-Hill Book Company, Inc., New York, 488 p.

Forland, T, and W. A. Weyl, 1949, DISTRIBUTION OF HEAVY-METAL IONS IN SILICATES CONTAINING SEVERAL ANIONS OF DIFFERENT SIZE: Jour. Am. Ceram. Soc., v. 32, p. 267-272.

Harry, W. T. and C. H. Emeleus, 1960, MINERAL LAYERING IN SOME GRANITE INTRUSIONS OF S. W. GREENLAND: Rept. 21st Int. Geol. Cong., part 14, p. 172-181.

Hess, H. H., 1960, STILLWATER IGNEOUS COMPLEX, MONTANA: Geol. Soc. Am. Memoir 80, 230 p.

Howell, J. V., 1957, GLOSSARY OF GEOLOGY AND RELATED SCIENCES: National Academy of Sciences, National Research Council, Publication 501.

Jaffe, H. W., D. Gottried, C. L. Waring and H. W. Worthing, 1959, LEAD-ALPHA AGE DETERMINATION OF ACCESSORY MINERALS OF IGNEOUS ROCKS (1953-1957): U.S. Geol. Survey Bull. 1097-B, p. 65-148.

Larsen, E. S., Jr. and W. M. Draisin, 1950, COMPOSITION OF THE MINERALS IN THE ROCKS OF THE SOUTHERN CALIFORNIA BATHOLITH: Rept. 18th Int. Geol. Congress, 1948, Part II, Proc. Sect. A, p. 66-79.

MacKenzie, Wm. S., 1954, THE ORTHOCLASE-MICROLINE INVERSION: Min. Mag. v. 30, no. 224, p. 354-366.

Nockolds, S. R. and R. L. Mitchell, 1948, THE GEOCHEMISTRY OF SOME CALEDONIAN PLUTONIC ROCKS: A STUDY IN THE RELATIONSHIP BETWEEN THE MAJOR AND TRACE ELEMENT OF IGNEOUS ROCKS AND THEIR MINERALS: Trans. Roy. Soc. of Edinburgh, 51, Part II, no. 20, p. 533-575.

Poldervaart, A. and W. H. Taubeneck, 1959, LAYERED INTRUSIONS OF THE WILLOW LAKE TYPE: Bull. Geol. Soc. Am., v. 70, p. 1395-1397.

Rose, A. W., 1957, TRACE ELEMENTS IN SULFIDE MINERALS FROM THE CENTRAL MINING DISTRICT, NEW MEXICO, AND THE BINGHAM DISTRICT, UTAH: 264 p., unpublished Ph.D. Thesis, California Institute of Technology.

Sen, N., S. R. Nockolds and R. Allen, 1959, TRACE ELEMENTS IN MINERALS FROM ROCKS OF THE SOUTHERN CALIFORNIA BATHOLITH: Geochim. et Cosmochim. Acta, v. 16, pp. 58-78.

Sharp, B. J., 1958, MINERALIZATION IN THE INTRUSIVE ROCKS IN LITTLE COTTONWOOD CANYON, UTAH: Bull. Geol. Soc. Am., v. 69, p. 1415-1430.

Slawson, W. F. and M. P. Nackowski, 1959, TRACE LEAD IN POTASH FELDSPARS ASSOCIATED WITH ORE DEPOSITS: Econ. Geol., v. 54, p. 1543-1555.

Stewart, D. B., 1957, THE SYSTEM $CaAl_2Si_2O_8$-SiO_2-H_2O: Year Book 56, Carnegie Institution of Washington, p. 214-216.

Tauson, L. V. and L. A. Kravchenko, 1956, CHARACTERISTICS OF LEAD AND ZINC DISTRIBUTION IN MINERALS OF CALEDONIAN GRANITES OF THE SUSAMYR BATHOLITH IN CENTRAL TIANSHAN: Geochemistry (in translation) no. 1, p. 78-88. Pub. 1960.

Tuttle, O. F., 1952, OPTICAL STUDIES ON ALKALI FELDSPARS: Am. Jour. Sci., Bowen Volume, p. 553-568.

Tuttle, O. F. and N. L. Bowen, 1958, ORIGIN OF GRANITE IN THE LIGHT OF EXPERIMENTAL STUDIES IN THE SYSTEM $NaAlSi_3O_8$-$KalSi_3O_8$-SiO_2-H_2O: Geol. Soc. of Am., Memoir 74, 153 p.

Wager, L. R. and W. A. Deer, 1939, GEOLOGICAL INVESTIGATIONS IN EAST GREENLAND. PART III. THE PETROLOGY OF THE SKAERAARD INTRUSION, KANGERDLUGSSUAK: Medd. Grønland, v. 105, no. 4, p. 1-352.

Wager, L. R., G. M. Brown and W. J. Wadsworth, 1960, TYPES OF IGNEOUS CUMULATES: Jour. of Pet., v. 1, no. 1, p. 73-85.

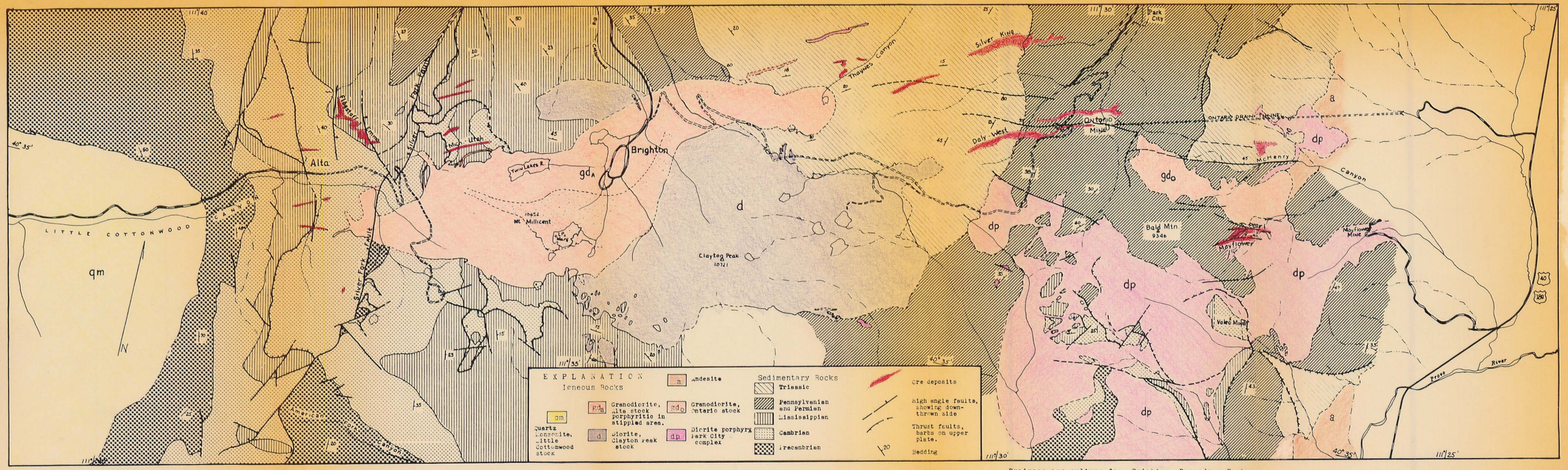
Warren, B. E. and A. G. Pincus, 1940, ATOMIC CONSIDERATIONS OF IMMISCIBILITY IN GLASS SYSTEMS: Jour. Amer. Ceram. Soc., v. 23, p. 301-304.

Wedepohl, K. H., 1953, UNTERSUCHUNGEN ZUR GEOCHEMIE DES ZINKS: Geochim. et Cosmochim. Acta, v. 3, p. 93-142.

Wilson, Clark L., 1960, PARK CITY MINING DISTRICT: Intermountain Association of Petroleum Geologists, 10th ann. field conf. guidebook.

Yoder, H. S., D. B. Stewart and J. R. Smith, 1957, TERNARY FELDSPARS: Yearbook 56, Carnegie Institution of Washington, p. 206-214.

PLATE I

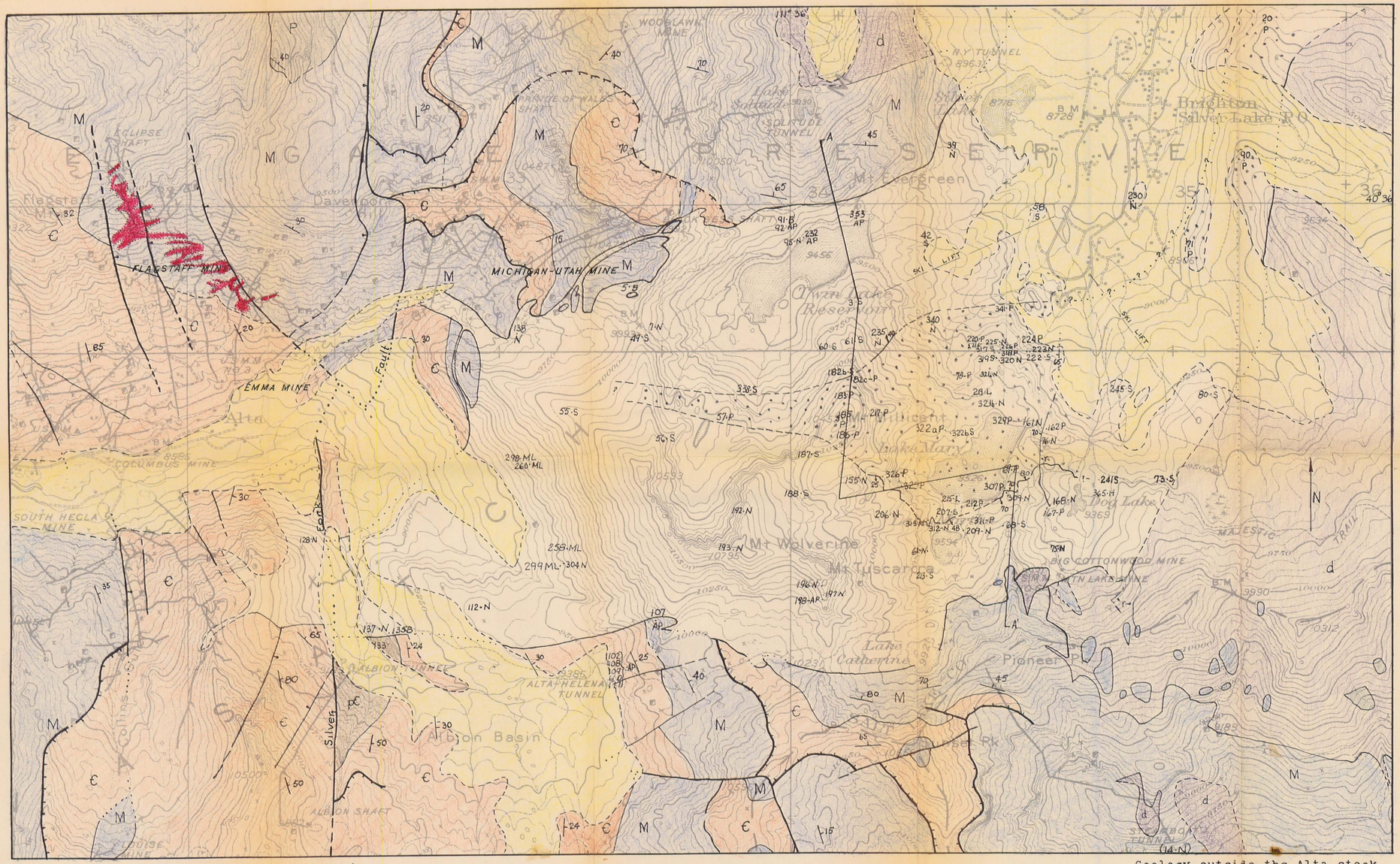


Geology after Boutwell (1912), Calkins and Butler (1943); Crittenden et al. (1952), and C.L. Wilson (1960); modified by J.C. Wilson in 1961.

GEOLOGIC MAP OF THE PARK CITY-COTTONWOOD AREA, UTAH

Drainage and culture from Brighton, Dromedary Peak, Heber, Park City East, and Park City West quadrangles published by the U. S. Geological Survey in 1955.

PLATE 2



Base map adapted from 1:25,000 Cottonwood quadrangle, 1938, U.S. Geol. Survey.

Geology outside the Alta stock from Calkins and Butler (1943). Geology of the Alta stock by John C. Wilson 1958-1960.

GEOLOGIC MAP OF THE ALTA STOCK, UTAH

EXPLANATION

Sedimentary Rocks

- Q — Quaternary
- P — Pennsylvanian and Permian
- M — Mississippian
- C — Cambrian
- pC — Precambrian

Igneous Rocks

- r — Rhyolite dikes
- g — Granodiorite of the Alta stock, porphyritic facies stippled
- d — Diorite of the Clayton Peak stock

Ore Deposits

- TC — Approximate outline of stopes

- High angle fault showing downthrown side
- Overthrust, barbs on overthrust side

A A' Structure section, Plate 6

219-L Sample locality showing rock type

- AP Aplite-pegmatite dikes
- B Border rock
- H Hornblende joint fillings
- L Leucocratic quartz monzonite dikes
- ML Mafic layered granodiorite
- N Nonporphyritic granodiorite
- P Porphyritic granodiorite
- S Subporphyritic granodiorite

contour interval 50 feet

0 — 5000

Scale in Feet

PLATE 3

Brighton

40°36'

Alta

111° 36'

EXPLANATION

- Strike and dip of foliation
- Strike of vertical foliation
- 20 ← Plunge of lineation
- Horizontal lineation
- ? ← Probable strike of poorly defined lineation
- 30 Mafic layered granodiorite

0 2000 Feet

LINEATION AND FOLIATION

EXPLANATION

60 Strike and dip of joints

Strike of vertical joints

Joints with silicate or sulfide minerals on surface

0 2000

Feet

Brighton

Alta

40°36'

111° 36'

JOINT MEASUREMENTS IN THE ALTA STOCK